PUBLICATION 79-15

DOE/JPL-1012-3
Distribution Category UC-63b

DEPARTMENT OF ENERGY

LSA
LOW-COST SOLAR ARRAY
PROJECT

(NASA-CR-158651) LOW-COST SOLAR ARRAY (LSA) PROJECT Quarterly Report, Apr. - Jun. 1978 (Jet Propulsion Lab.) 60 p HC A04/MF A01 CSCL 10A

N79-24458

Unclas
G3/44 22325

Project QUARTERLY REPORT-9

FOR THE PERIOD APRIL 1978–JUNE 1978

5101-99

DEPARTMENT OF ENERGY

LSA
LOW-COST SOLAR ARRAY
PROJECT

Project QUARTERLY REPORT - 9

FOR THE PERIOD APRIL 1978 - JUNE 1978

5101-99

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

(JPL PUBLICATION 79-15)

ABSTRACT

This report describes progress made by the Low-Cost Solar Array Project during the period April through June 1978. It includes reports on silicon material processing, large-area silicon sheet development, encapsulation materials testing and development, Project engineering and operations activities, and manufacturing techniques, plus the steps taken to integrate these efforts.

CONTENTS

Figures

Tables

SECTION I

INTRODUCTION AND PROJECT OVERVIEW

A. INTRODUCTION

This report describes the activities of the Low-Cost Solar Array Project during the period April through June 1978. The LSA Project is assigned responsibility for advancing solar array technology while encouraging industry to reduce the price of arrays to a level at which photovoltaic electric power systems will be competitive with more conventional power sources early in the next decade. Set forth here are the goals and plans with which the Project intends to accomplish this and the progress that has been made during the quarter.

The Project objective is to develop the national capability to produce low-cost, long-life photovoltaic arrays at a rate greater than 500 megawatts per year and at a price of less than $500 (in 1975 dollars) per peak kilowatt by 1986. The array performance goals include an efficiency greater than 10% and an operating lifetime in excess of 20 years.

B. PROJECT OVERVIEW

In the Project Analysis and Integration Area, the Planning and Integration effort has selected the Lifetime Cost and Performance model computer code. It has also provided extensive support for the preparation of the Tsongas Request for Proposal, and is developing a proposal evaluation methodology to apply SAMICS to the proposals. Long range program planning was also a very active area.

SAMICS -- Uniform Costing Standards validation activities continued in the Array Technology Cost Analysis effort. Presentations of the SAMICS methodologies were made at national meetings and reports describing SAMIS -- Computer Simulation Program are in preparation.

In the Economics and Industrialization effort, draft final reports have been received on the Bechtel Corp. estimates of flat-plate photovoltaic central power systems, and on the Gnostics Concepts, Inc., investment decision analysis. Indoor LAPSS and outdoor data acquisition have been completed in an experimental study to verify a procedure for adjusting module power output for the effects of insolation and temperature. In addition, a paper entitled "Effects of Design and Cost on Flat-Plate Solar Photovoltaic Arrays for Terrestrial Central Power Applications" was presented, a major support effort was given to the SERI "Photovoltaic Venture Analysis," and planning support was completed for a presentation at DOE on silicon materials.

The Silicon Material Task reported progress in various areas during the quarter. Battelle submitted an integrated plan for design and fabrication of an EPSDU sized at 50 MT/yr of Si, and Union Carbide reported continuing progress on its 100 MT/yr EPSDU. Motorola initiated design studies for a mini-EPSDU sized at 1 kg/hr of Si.

Dow Corning established purity goals for raw materials and silicon at various stages of the process train, and SRI International conducted experiments on the reduction of SiF_4 by Na. Design and preparation of specifications continued at Westinghouse for hardware to be used in the Si production process demonstration using an arc heater process. AeroChem Research conducted experiments with the nonequilibrium hydrogen atom plasma jet using $SiCl_4$ as the reactant. AeroChem also reported flame experiments using Na and $SiCl_4$ under a variety of conditions of pressure, temperature, and flow velocity. Results obtained by J. C. Schumacher from experiments in a fluidized bed indicate that the decomposition of $SiHBr_3$ to form Si can be controlled to avoid deposition on the reactor walls and the formation of fine particles.

Westinghouse and Dow Corning completed Phase II of their effort to determine effects of impurities and process steps on properties of Si and performance of solar cells. C. T. Sah, also working on effects of impurities, completed its first annual report. Materials Research performed X-ray analyses on copper-doped, copper/titanium-doped, and titanium-doped wafers before and after diffusion of phosphorous.

JPL studies included test runs in the continuous flow pyrolyzer, experiments in a 2-in-diameter fluidized bed reactor, design of a 1-in-diameter quartz reactor system, and completion of the mathematical modeling of transport processes in the continuous-flow pyrolyzer.

AeroChem Research, working on a model and computer code to describe silicon production processes, concentrated on obtaining working versions of particle "chemistry" routines within the large code. Lamar University continued analysis of process system properties for Si source materials, obtained final experimental values for gas-phase thermal conductivity of particular Si source materials, and continued chemical engineering analysis of the Union Carbide SiH_4 process.

Also during the quarter, Los Alamos Scientific Laboratory initiated efforts to study the removal of impurities from SiH_4 by means of a laser.

The Large-Area Silicon Sheet Task reported progress in five areas: shaped ribbon technology, supported film technology, ingot technology, and contact material.

In shaped ribbon technology, Mobil Tyco emphasized production and evaluation of demonstration runs, while Motorola stressed growth rates.

Coors and Honeywell are both processing slotted substrates of various configurations in their supported film technology contracts, and RCA Labs accomplished epitaxial growth on "upgraded metallurgical grade" silicon.

Crystal Systems achieved a high degree of crystallinity in the square ingots cast. Developments in the advanced Czochralski process were reported by Kayex Corp. (two recharges demonstrated), Siltec Corp., (furnace design completed), Varian (five crystals grown with a total throughput of 48 kg).

In contact material contracts, Battelle Labs reported on a promising die material, Coors Porcelain studied a mixture of fused mullite and fused silica, Eagle Picher conducted some initial sessile drop experiments, and RCA Labs studied the thermal stability of CVD SiO_xN_y layers in contact with molten silicon.

In the Encapsulation Task, an add-on to the Springborn contract was executed and agreement was reached on the final version of Springborn's second annual report. A program plan representing joint ITW/Endurex involvement was also approved. An add-on to the Battelle contract to do a life prediction study was executed and a draft of a report on encapsulation methods and materials was approved. Motorola's final report on antireflective coatings was distributed.

SPIRE completed planned modifications to the electrostatic bonder and started work on defining optimum materials and processes. An amended version of Dow Corning's Phase I program plan was approved and experimental activities initiated. The Rockwell Science Center annual report was received and includes a discussion of a relatively new methodology termed Preventive Nondestructive Evaluation and its adaptation to LSA applications.

JPL began an in-house effort to study the processing of polymers in the various encapsulation systems being tested at JPL and by Encapsulation Task contractors.

In the Production Process and Equipment Area, progress was reported in five areas: surface preparation, junction formation, metallization, assembly, and advanced module development.

Progress in surface preparation included production of layers of titanium dioxide for AR coating applications; advances in texture etching technology; and production of spray-on AR coating solutions.

In work on junction formation, a Silox reactor for doped oxides processing used in the formation of backsurface field regions gave results comparable to those achieved with a cold-wall open-tube reactor. This reactor is more conservative with materials and is better suited to the processing of continuous ribbons of webbed silicon.

Metallization of silicon wafers was demonstrated to be efficient with negative silk-screening, electroless nickel-plating, and wave soldering. This process may lend itself well to automation and therefore be very cost effective.

Work is being pursued on the premise that ultrasonic seam bonding of foil interconnects to the cell metallization may be a potentially higher throughput, lower cost method of interconnection. Using an industrial robot for automated array assembly, arc spraying of interconnects, and a system for trimming solar cells are also being investigated.

Test results on shingle modules are presently encouraging.

Engineering Area activities stressed array design guidelines, reliability-durability requirements, and array specifications and standards.

Bechtel and Boeing, working in the area of design guidelines, began work on their draft final reports. Burt, Hill, Kosar, Rittleman Associates was selected for negotiations of the study contract concerning the residential module requirements study. Work on application of non-linear structural analysis to support module structural design centered on the use of three different computer programs, and effort was also spent on modifying the computer program used to determine series/parallel combinations of cells and modules in order to provide for multiple failures in a non-varying sequence.

In the area of reliability-durability requirements, the final group of hail tests of Block III and advanced module designs was completed, the second phase of module bias-humidity testing using Block II minimodules was completed, and surface soiling exploratory tests were conducted on Block II minimodules. A contract was negotiated with DSET, Inc., (Phoenix) to perform accelerated (8X) sunlight exposure of minimodules.

A new module design requirement is described in JPL internal document 5101-65, "Photovoltaic Module Design, Qualification and Testing Specification." A major effort was also made during the quarter to examine various photovoltaic definitions and design criteria.

In the Operations Area, all contractors delivered Block III modules for the Large-Scale Production Task. The total of 36 kW delivered was only 35% of the amount projected by the contractors at the beginning of the quarter, apparently the result of under estimating quality assurance requirements for production.

In environmental testing, three Type W Block II modules underwent a final exploratory humidity-heat test. Of the Block III modules, four Type Y and five Type U modules passed the standard temperature cycling, humidity, and pressure cycling test series. Another set of U modules, designed for military use, was qualification tested. Five vendor sets of modules were tested for temperature coefficients, and some of these were also electrically tested to verify vendors' power measurements.

Environmental tests performed on automated array assembly developmental modules (Task 4) included: Type O, full qualification; Type YH, full qualification; Type K, temperature and humidity cycling; and Type M, full qualification. Four commercial Type CN modules were subjected to the standard temperature cycling test and all failed.

Field testing activity during the quarter consisted primarily of consolidation. In addition to acquiring basic data, effort was devoted to improving operating procedures, planning for future module deployments, writing an update report, and developing plans for solutions to some of the testing problems.

The Operations Area also completed testing and distribution of the Block III reference cells, and the Block II/III reference cell intercomparison was completed for all vendors.

Failure analysis activity included filing of 32 new problem/ failure reports and closure of 28 problem/failure analyses.

SECTION II

PROJECT ANALYSIS AND INTEGRATION AREA

A. PLANNING AND INTEGRATION

The Lifetime Cost and Performance (LCP) model computer code has been selected. The economic model has been completed and various options are being examined for the array power model.

Extensive support has been provided for the preparation of the Tsongas RFP. In addition, a proposal evaluation methodology is being developed to apply SAMICS to the proposals in order to independently estimate the cost savings resulting from the processes proposed in the Tsongas RFP responses.

Long range program planning was a very active area this quarter with numerous quick response inquiries from DOE being handled.

B. ARRAY TECHNOLOGY COST ANALYSIS

SAMICS -- Uniform Costing Standards validation activities continued, with detailed comparisons of SAMICS and IPEG results. Presentations of the SAMICS methodology were made at the 13th IEEE Photovoltaics Specialists Conference and at the ORSA/TIMS (Operations Research Society of America/The Institute of Management Sciences) Joint National Meeting.

Reports describing SAMIS -- Computer Simulation Program, JPL internal documents 5101-60 and 5101-71, are in preparation for publication.

Optimization of the SAMIS III simulation computer program has reduced the price per run from $650 to approximately $100. Additional improvements are anticipated.

The update of the Price Allocation Guidelines was completed. The results were presented at the 9th LSA Project Integration Meeting and are published in the JPL internal document 5101-68.

C. ECONOMICS AND INDUSTRIALIZATION

The draft final report has been received for the Bechtel Corp. estimate of five designs of a flat-plate photovoltaic central power system. Preliminary results indicate the critical importance of the non-module system costs.

Indoor LAPSS and outdoor data acquisition have been completed in the experimental study to verify a procedure for adjusting module power output for the effects of insolation and temperature. A data reduction program has been developed for the PDP11 and initial test runs have been made. A programming effort is in progress to automate all data analysis for both the indoor and outdoor data.

A paper titled "Effects of Design and Cost on Flat-Plate Solar Photovoltaic Arrays for Terrestrial Central Power Applications" was presented at the 13th IEEE Photovoltaic Specialists Conference.

The Gnostics Concepts, Inc., Investment Decision Analysis draft final report has been received and a review is in progress.

A major effort has been dedicated to the support of the SERI "Photovoltaic Venture Analysis," which is being conducted by SERI for DOE with close cooperation of the other program prime contractors.

Planning support was completed for a presentation on silicon materials scheduled at DOE for June 29 and 30, 1978.

SECTION III

TECHNOLOGY DEVELOPMENT AREA

A. SILICON MATERIAL TASK

The objective of the Silicon Material Task is to establish by 1986 an installed plant capability for producing silicon (Si) suitable for solar cells at a rate equivalent to 500 megawatts (peak) of solar arrays per year and at a price of less than $10 per kilogram. The program formulated to achieve this objective is based on the conclusion that the price goal cannot be reached if the process used is essentially the same as the present commercial process for producing semiconductor-grade Si. Consequently, it is necessary that different processes be developed for producing either semiconductor-grade Si or a less pure, but utilizable, Si material (i.e., a solar-cell-grade Si).

1. Technical Goals

Solar cells are presently fabricated from semiconductor-grade Si, which has a market price of about $65 per kilogram. A drastic reduction in price of material is necessary to meet the economic objectives of the LSA Project. One means for meeting this requirement is to devise a process for producing a Si material which is less pure than semiconductor-grade Si. However, the allowance for the cost of Si material in the overall economics of the solar arrays for LSA is dependent on optimization trade-offs, which concomitantly treat the price of Si material and the effects of material properties on the performance of solar cells. Accordingly, the program of the Silicon Material Task is structured to provide information for the optimization trade-offs concurrently with the development of high-volume, low-cost processes for producing Si.

2. Organization and Coordination

The Silicon Material Task effort is organized into four phases. As Table 3-1 indicates, Phase I is divided into four parts. In Part I the technical feasibility and practicality of processes for producing semiconductor-grade Si will be demonstrated. In Part II the effects of impurities and of various processing procedures on the properties of single-crystal Si material and the performance characteristics of solar cells will be investigated. This body of information will serve as a guide in developing and assessing processes (in Part III) for the production of solar-cell-grade Si. The process developments in Parts I and III will be accomplished through chemical reaction, chemical engineering, energy-use, and economic studies. In Part IV of Phase I, the relative commercial potentials of the various Si-production processes developed under Parts I and III will be evaluated. Thus, at the end of Phase I a body of information will have been obtained for optimization trade-off studies, and the most promising process will have been selected.

Table 3-1. Organization of the Silicon Material Task Effort

Phase/Part	Objective
Phase I	Demonstrate the technical feasibility and practicality of processes for producing Si.
Part I	Establish the practicality of a process capable of high-volume production of seimconductor-grade Si.
Part II	Investigate the effects of impurities and of various processing procedures on the properties of single-crystal Si material and the performance characteristics of solar cells.
Part III	Establish the practicality of a process capable of high-volume production of solar-cell-grade Si.
Part IV	Evaluate the relative commercial potential of the Si-production processes developed under Phase I.
Phase II	Obtain process scale-up information.
Phase III	Conduct EPSDU operations to obtain technical and economic evidence of large-scale production potential.
Phase IV	Design, install, and operate a full-scale commercial plant capable of meeting the production objective.

Phase II will be to obtain process scale-up information. This will be derived from experiments and analyses involving mass and energy balances, process flows, kinetics, mass transfer, temperature and pressure effects, and operating controls. The basic approach will be to provide fundamental scientific and engineering information from which valid extrapolations usable for plant design can be made; applicable scale-up correlations will also be used. This body of scale-up information will then provide the necessary basis for the design, construction, and operation of Experimental Process System Development Units (EPSDU).

Since the installation and operation of a commercial chemical process plant that incorporates a new process involves high risks, EPSDU will be used to obtain technical and economic evidence of large-scale production potential. In the EPSDU phase (i.e., Phase III) there will be opportunities to correct design errors; to determine energy consumption; to establish practical operating procedures and production conditions for process optimization and steady state operation; and to more realistically evaluate the requirements for instrumentation, controls, and on-line analyses.

In the final phase of the Silicon Material Task (i.e., Phase IV), a full-scale commercial plant capable of meeting the production objective will be designed, installed, and operated. The EPSDU and the commercial plant will be operated concurrently for some time so as to permit the use of the EPSDU for investigations of plant operations, i.e., for problem-solving and for studies of process optimization.

Additional basic chemical and engineering investigations to respond to problem-solving needs of the Silicon Material Task will be conducted in supporting efforts. These supporting subtasks will be accomplished under contract and by an in-house JPL program.

3. Silicon Material Task Contracts

Sixteen contracts are in progress and are listed in Table 3-2.

4. Silicon Material Task Technical Background

a. Processes for Producing Semiconductor-Grade Si

1) Production of Si by Zn Reduction of $SiCl_4$ -- Battelle. The contract with Battelle Columbus Laboratories is for development of the reaction for the Zn reduction of silicon tetrachloride ($SiCl_4$) using a fluidized bed reactor as an economical means for producing Si. Based on calculations by Battelle and Lamar University, this process has the potential for a total product cost between $9.12 and $9.68/kg Si for a 1000 MT/yr plant.

2) Production of Si from SiH_4 Prepared by Redistribution of Chlorosilanes -- Union Carbide. The Union Carbide contract is for the development of processes for the production of silane (SiH_4) and for the subsequent deposition of Si from SiH_4. The SiH_4 process includes systems for the redistribution of chlorosilanes and the hydrogenation of metallurgical grade Si and the by-product $SiCl_4$ to trichlorosilane ($SiHCl_3$), which can be used as a feed for redistribution. The free space reactor and the fluidized bed reactor are techniques being investigated as the means for Si deposition.

3) Production of Si by SiF_4/SiF_2 Transport -- Motorola. The Motorola contract is for the development of a process for the conversion of metallurgical-grade Si into semiconductor-grade Si using $SiF_4/(SiF_2)_x$ transport purification reaction steps.

Table 3-2. Silicon Material Task Contractors

Contractor	Technology Area
AeroChem Research Princeton, New Jersey (JPL Contract No. 954560)	Nonequilibrium plasma jet process
AeroChem Research Princeton, New Jersey (JPL Contract No. 954777)	Si halide-alkali metal flames process
AeroChem Research Princeton, New Jersey (JPL Contract No. 954862)	Model of silicon hydride and halide reactions
Battelle Columbus, Ohio (JPL Contract No. 954339)	$Zn/SiCl_4$ fluid bed reactor process
Dow Corning Hemlock, Michigan (JPL Contract No. 954559)	Electric arc furnace process
Lamar University Beaumont, Texas (JPL Contract No. 954343)	Technology and economic analyses
Los Alamos Scientific Laboratory Los Alamos, New Mexico (NASA Defense Purchase Request No. WO 8628)	Laser purification of SiH_4
Materials Research Salt Lake City, Utah (JPL PO No. JR-672583)	X-ray analysis of silicon wafers
Motorola Phoenix, Arizona (JPL Contract No. 954442)	SiF_4/SiF_2 transport process
National Bureau of Standards Washington, D.C. (NASA Defense Purchase Request No. WO 8604)	Impurity concentration measurements
Sah, C. T. Associates Urbana, Illinois (JPL Contract No. 954685)	Effects of impurities

Table 3-2. Silicon Material Task Contractors
(Continuation 1)

Contractor	Technology Area
Schumacher, J. C. Oceanside, California (JPL Contract No. 954914)	High-velocity continuous flow reactor process
SRI International Menlo Park, California (JPL Contract No. 954471)	Na reduction of SiF_4 process
Union Carbide Sisterville, West Virginia (JPL Contract No. 954334)	Silane/Si process
Westinghouse Pittsburgh, Pennsylvania (JPL Contract No. 954331)	Effects of impurities on solar cells
Westinghouse Pittsburgh, Pennsylvania (JPL Contract No. 954589)	Plasma arc heater process

b. Effects of Impurities and Processing on Solar Cell Performance

1) Determination of the Effects of Impurities and Process-Steps on Properties of Si and the Performance of Solar Cells -- Westinghouse/Dow Corning. Phase II of this contract consists of five tasks: (1) The effects of processing-steps, such as heat treatment, gettering, and crystal growth parameters, will be determined in conjunction with the impurity effects. (2) The combined effects of impurities and high boron (B) concentrations on solar cell performance will be examined. (3) The effects of impurities on n-type, phosphorus-doped Si will be determined; these data will be compared with those for p-type, B-doped Si material. (4) The impurity matrix for n-type Si will be expanded, especially in two areas: measurement and modeling for material containing two or more impurities and study of impurities which may contaminate the Si during the Si production process. (5) The effects of oxygen and carbon interactions with the impurities will be studied.

2) Effect of Impurities -- C. T. Sah Associates. Deep level transient spectroscopy measurements are to be used for correlations with the development of a model for solar cell performance.

3) X-Ray Analysis of Si Wafers -- Materials Research. This is for a non-destructive study of the crystallographic structure defects in Si wafers deliberately doped with impurities.

c. Processes for Producing Solar-Cell-Grade Si

1) Production of Si Using Submerged Arc Furnace and Unidirectional Solidification Process -- Dow Corning. The Dow Corning contract is for the development of a process for improving the purity of Si produced in the arc furnace by using purer raw materials and for the further purification of the Si product by unidirectional solidification.

2) Production of Si from H_2SiF_6 Source Material Using Na Reduction of SiF_4 Process -- SRI International. This contract is for the development of a two-step process for the production of Si. The steps are (1) the reduction of silicon tetrafluoride (SiF_4) by sodium (Na) to produce high-purity Si and (2) the further purification of this product.

3) Production of Si Using Arc Heater Process for Reduction of $SiCl_4$ by Na -- Westinghouse. This contract with Westinghouse is for the development of an electric arc heater process for the production of Si using the reaction for the reduction of $SiCl_4$ by Na.

4) Production of SiH_4 or Si Using a Nonequilibrium Plasma Jet for the Reduction of Chlorosilanes -- AeroChem Research. The objective of this program is to determine the feasibility of the production of high purity SiH_4 or solar-cell-grade Si using a nonequilibrium hydrogen atom plasma jet. Reactions of hydrogen atoms in the plasma jet with chlorosilanes are being studied.

5) Production of Si Using Si Halide-Alkali Metal Flames -- AeroChem Research. The objective of this contract is to determine the feasibility of the use of flame reactions involving Si halides and alkali metals for producing Si.

6) High-Velocity, Continuous Flow Reactor for Producing Si -- Schumacher. The objective of this contract is to determine the feasibility of using bromosilanes as the appropriate intermediates to produce Si.

d. Supporting Contracts

1) Evaluation of Si Production Processes -- Lamar University. The objective of this contract is to evaluate the potentials of the processes being developed in the program of the Silicon Material Task. The economic evaluations will be based upon analyses of process-system properties, chemical engineering characteristics, and costing-economics. The evaluations will be performed during all phases of the Task, using information which becomes available from the various process development contracts.

2) Impurity Concentration Measurements -- National Bureau of Standards. Methods for measurements of impurities at ppba levels are to be developed.

3) Model of Si-Producing Reactions -- AeroChem Research. This contract is for the formulation of a model and a computer code for the description of several of the Si processes now under development.

4) Purification of SiH_4 by Laser Apparatus -- Los Alamos Scientific Laboratory. This is a study of the removal of impurities, particularly boron, phosphorus, and arsenic, from SiH_4 using a laser.

5. Summary of Progress

a. Production of Si by Zn Reduction of $SiCl_4$ -- Batteile. An integrated plan for the design and fabrication of an EPSDU sized at 50 MT/yr of Si was delivered to JPL. This plan is under evaluation by a Silicon Material Task team, which held a formal technical review of the proposed process in June. The schedule allows one year for installation, one year for debugging, and then operation. A number of advances were made in the experimental support work, including operation of the zinc vaporizer at the rate required for operation in the 50 MT/yr installation.

b. Production of Si from SiH_4 Prepared by Redistribution of Chlorosilanes -- Union Carbide. Progress on the 100 MT/yr EPSDU continued, with preparation and approval of the procurement package, and approval by the Non-competitive Source Board. A preliminary conceptual design for the fluidized bed pyrolysis of SiH_4 in the EPSDU was completed. In the experimental effort, the demonstration of continuous, integrated production of SiH_4 from metallurgical-grade Si and H_2 was accomplished for more than 10 days of continuous operation. A series of experiments was conducted to obtain information on the mechanism of SiH_4 pyrolsis, and production of the three Si product forms obtained -- plate, powder, and fibers -- was found to be controllable.

c. Production of Si by SiF_4/SiF_2 Transport -- Motorola. Design studies were initiated for a mini-EPSDU sized at 1 kg/hr of Si product. An engineering subcontractor, R. Katzen Associates, was hired to assist in preparing a process design due for delivery to JPL by November 1978. An updated process plant cost estimate for a 1000-MT/yr Si capacity gave a product cost of $7.71/kg Si.

d. Production of Si Using Submerged Arc Furnace and Unidirectional Solidification Process -- Dow Corning. Purity goals were established for raw materials and silicon at various stages of the process train based upon current knowledge of the purity required for solar-grade silicon. Experimental studies were carried out on a variety of carbonaceous reductants for quartz. Preliminary work on sugar indicates that sugar char is of high purity and has a suitable (nongraphitic) structure. Lignite and petroleum coke were eliminated from further consideration on the basis of their impurity content.

e. Production of Si from H_2SiF_6 Source Material Using Na Reduction of SiF_4 -- SRI International. Experiments were conducted on the reduction of SiF_4 by Na, producing in this period about 6 kg of reaction product containing about 0.6 kg of Si. Aqueous leaching of this reaction product was studied. The resulting silicon was found by emission spectroscopy to be fairly pure, although traces of calcium and copper were found in some samples.

f. Production of Si Using Arc Heater Process for Reduction of $SiCl_4$ by Na -- Westinghouse Electric. Design and preparation of specifications continued for hardware to be used in the process demonstration, and procurement of components and equipment was started. Analysis and detailed design of the reactor was completed. For the three experimental support tasks, fabrication of the test systems continued. Construction of the test system for the kinetics task was completed, and shakedown tests started.

g. Production of SiH_4 or Si Using a Nonequilibrium Plasma Jet for the Reduction of Chlorosilanes -- AeroChem Research. Experiments were conducted with the nonequilibrium hydrogen atom plasma jet using $SiCl_4$ as the reactant, in which Si was deposited in the form of amorphous and polycrystalline films. Films were prepared which adhered strongly to various substrates. Using SiH_4 as the reactant, loose powdery deposits of Si were obtained, confirming earlier results. Modifications were made to the apparatus to make it more versatile and to permit doping of the films.

h. Production of Si Using Si Halide-Alkali Metal Flames -- AeroChem Research. Experiments using Na and $SiCl_4$ were made under a variety of conditions of pressure, temperature, and flow velocity. Comparative experiments using 300°K Ar and 1000°K H_2/Ar diluents were performed with few differences found in deposition rates or product characteristics. Silicon from both sets of experiments was found to contain small amounts of iron and other metal impurities. In an experiment with Na and SiF_4 in an unheated reactor tube, mostly Na_2SiF_6 was produced, with only a small yield of Si.

i. Production of Si from Bromosilanes -- J. C. Schumacher. Experiments were made in a fluidized bed on the decomposition of tribromosilane ($SiHBr_3$) and on the reduction of $SiHBr_3$ with H_2. The results indicate that in the decomposition of $SiHBr_3$, two different reactions take place, one reaction dominating in a relatively low temperature range and consisting of the formation of Si, silicon tetrabromide ($SiBr_4$), and H_2. In the range of 970°K to 1,170°K, yields of Si in the range of 72% to more than 90% of the stoichiometric amounts were obtained. No polymer formation was noted, and very little or no deposition of Si occurred on the reactor walls, the degree of wall deposition being controllable by temperature. No production of fine particles by homogeneous nucleation was noted. In other experiments, it was found that the reaction could be reversed, offering the possibility of a closed-loop process consisting of conversion of metallurgical-grade Si, $SiBr_4$, and H_2 to $SiHBr_3$ and subsequent decomposition of the $SiHBr_3$ (after purification) to solar-cell-grade Si, $SiBr_4$, and H_2.

j. Determination of the Effects of Impurities and Process Steps on Properties of Si and the Performance of Solar Cells -- Westinghouse/Dow Corning. The Phase II effort was completed, the objective being to investigate the effects of various processes, metal contaminants, and contaminant/process interactions on the performance of terrestrial Si solar cells. The Phase II Summary Report was completed, and the Phase III Program Plan and Baseline Spending Plan were developed and submitted. One conclusion of the Phase II effort is that impurity-induced performance loss is primarily due to reduction in the base diffusion length. Also, many metal contaminants, e.g., Ti, V, Cr, and Mn, produce considerably less cell performance reduction in n-base devices than in p-base devices.

k. Effects of Impurities -- C. T. Sah Associates. The first annual report was completed. The transmission line equivalent circuit model was completed to allow computation of the exact steady-state characteristics of one-dimensional silicon solar cells. Also, the effects of emitter diffusion profiles on Si solar cell performance were investigated.

l. X-Ray Analysis of Silicon Wafers -- Materials Research. X-ray analyses were performed on copper-doped, copper/titanium-doped, and titanium-doped wafers before and after diffusion of phosphorus. In the cases of Cu and Cu/Ti doping, the quantities of precipitate particles were greater after the diffusion process. In the case of Ti doping, precipitate particles were present after, but not before, the diffusion process. When Cu precipitates in the form of a Cu/Si/TiO_2 complex, it leaves no electrically active impurities in the junction, thus improving the solar cell performance.

m. JPL In-House Silicon Processing Technology. Two test runs were made in the continuous-flow pyrolyzer, marking the first use of SiH_4 in this apparatus. Each test lasted two hours. In each test, two very different morphologies of Si growth were observed, namely rust-colored spheres ranging in diameter from 0.1 to 0.3 micron and deposition of Si having a metallic appearance on the surface of an alumina tube (which was 100°C hotter than the SiH_4). These morphologies reveal information on the mechanism of SiH_4 pyrolysis and Si formation under various conditions.

A variety of experiments was conducted in a 2-in-diameter fluidized bed reactor. At temperatures greater than 660°C and SiH_4 concentrations less than 7 mole %, more than 90% of the SiH_4 was decomposed into Si and H_2. The Si formed a dense coating on the seed particles. Plugging of the reactor occurred in all tests. The design was modified to eliminate this problem.

A 1-in-diameter quartz reactor system was designed to study Si fines production.

In the reactor modeling area, the mathematical modeling of transport processes in the continuous-flow pyrolyzer was completed.

n. Development of a Model and Computer Code to Describe Silicon Production Processes -- AeroChem Research. During this report period, work centered on obtaining working versions of the particle "chemistry" (nucleation, coagulation, evaporation, and condensation) routines within the large code. The nucleation model in particular proved troublesome; efforts to debug it led to the writing of a smaller, independent nucleation code. This smaller code allows the model to be examined in more detail than is possible in the large code. A considerable effort was also spent during this period on streamlining the LAPP code to allow accommodation of the large number of equations describing particle processes. This effort has been successful in reducing memory requirements by as much as 50%.

o. Studies of Process Feasibility and Economic Analysis -- Lamar University. Analysis of process system properties was continued for Si source materials. Primary efforts centered on data collection, analysis, estimation, and correlation. Property data for $SiCl_4$ are reported for critical constants (temperature, pressure, volume, compressibility factor); vapor pressure; heat of vaporization; gas heat capacity, and liquid heat capacity. This substance is the source material in several processes under consideration for solar-cell-grade Si production.

Final experimental values for gas-phase thermal conductivity of the Si source materials SiH_4, dichlorosilane (SiH_2Cl_2), trichlorosilane ($SiHCl_3$), $SiCl_4$, and SiF_4 were reported in the temperature range of 25°C to 350°C. These final values reflect a refinement of previously reported preliminary values after complete calibration of the temperature-measuring apparatus.

Chemical engineering analysis of the Union Carbide SiH_4 process (Case C-Revised Process) was continued with primary efforts being devoted to the preliminary process design. Status and progress were reported for base case conditions, process flow diagram, reaction chemistry, and equipment design. Engineering design was in progress for the several distillation columns that separate the liquid chlorosilanes and provide purified SiH_4 product.

p. Purification of SiH_4 by Laser Apparatus -- Los Alamos Scientific Laboratory. This effort started in this period. Its objective is to study the removal of impurities, particularly boron, phosphorus, and arsenic, from SiH_4 by means of a laser. Effort was devoted to designing and providing the necessary experimental equipment, as well as to preparing the experimental plan.

B. LARGE-AREA SILICON SHEET TASK

The objective of the Large-Area Silicon Sheet Task is to develop and demonstrate the feasibility of several alternative processes for producing large areas of Si sheet material suitable for low-cost, high efficiency solar photovoltaic energy conversion. To meet the objective of the LSA Project, sufficient research and development must be performed on a number of processes to determine the capability of

each for producing large areas of crystallized Si. The final sheet growth configurations must be suitable for direct incorporation into an automated solar-array processing scheme.

1. Technical Goals

Current solar cell technology is based on the use of Si wafers obtained by slicing large Czochralski or float-zone ingots (up to 12.5 cm in diameter), using single-blade inner-diameter (ID) diamond saws. This method of obtaining single crystalline Si wafers is tailored to the needs of large volume semiconductor products (i.e., integrated circuits plus discrete power and control devices other than solar cells). Indeed, the small market offered by present solar cell users does not justify the development of Si high-volume production techniques which would result in low-cost electrical energy.

Growth of Si crystalline material in a geometry that does not require cutting to achieve proper thickness is an obvious way to eliminate costly processing and material waste. Growth techniques such as edge-defined film-fed growth (EFG), web-dendritic growth, chemical vapor deposition (CVD), etc., are possible candidates for the growing of solar cell material. The growing of large ingots with optimum shapes for solar cell needs (e.g., hexagonal cross-sections) requiring very little manpower and machinery would also appear plausible. However, it appears that the cutting of the large ingots into wafers must be done using multiple rather than single blades in order to be cost-effective.

Research and development on ribbon, sheet, and ingot growth plus multiple-blade and multiple-wire cutting initiated in 1975-1976 is in progress.

2. Organization and Coordination

At the time the LSA Project was initiated (January 1975) a number of methods potentially suitable for growing Si crystals for solar cell manufacture were known. Some of these were under development; others existed only in concept. Development work on the most promising methods is now being funded. After a period of accelerated development, the various methods will be evaluated and the best selected for advanced development. As the growth methods are refined, manufacturing plants will be developed from which the most cost-effective solar cells can be manufactured. The Large-Area Silicon Sheet Task effort is organized into four phases: research and development on sheet growth methods (1975-77); advanced development of selected growth methods (1977-80); prototype production development (1981-82); development, fabrication, and operation of production growth plants (1983-86).

3. Large-Area Silicon Sheet Task Contracts

Research and development contracts awarded for growing Si crystalline material for solar cell production are shown in Table 3-3. "Preferred" growth methods for further development during FY 1979-80 have been selected.

Table 3-3. Large-Area Silicon Sheet Task Contractors

Contractor	Technology Area
SHAPED RIBBON TECHNOLOGY	
Mobil-Tyco Solar Energy Waltham, Massachusetts (JPL Contract No. 954355)	Edge-defined film-fed growth (EFG)
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954376)	Ribbon growth Laser zone regrowth
Westinghouse Research Pittsburgh, Pennsylvania (JPL Contract No. 954654)	Dendritic web process
SUPPORTED FILM TECHNOLOGY	
Honeywell Corp. Bloomington, Minnesota (JPL Contract No. 954356)	Silicon on ceramic substrate
RCA Labs Princeton, New Jersey (JPL Contract No. 954817)	Epitaxial film growth on low-cost silicon substrates
INGOT TECHNOLOGY	
Crystal Systems, Inc. Salem, Massachusets (JPL Contract No. 954373)	Heat exchanger method (HEM), cast ingot, and multiwire fixed abrasive slicing
Kayex Corp. Rochester, New York (JPL Contract No. 954888)	Advanced CZ growth

Table 3-3. Large-Area Silicon Sheet Task Contractors (Continuation 1)

Contractor	Technology Area
INGOT TECHNOLOGY	
Siltec Corp. Menlo Park, California (JPL Contract No. 954886)	Advanced CZ growth
Texas Instruments Dallas, Texas (JPL Contract No. 954887)	Advanced CZ growth
Varian Vacuum Division Lexington, Massachusetts (JPL Contract No. 954374)	Multiblade slurry sawing
Varian Vacuum Division Lexington, Massachusetts (JPL Contract No. 954884)	Advanced CZ growth
DIE AND CONTAINER MATERIALS STUDIES	
Battelle Labs Columbus, Ohio (JPL Contract No. 954876)	Silicon nitride for dies
Coors Porcelain Golden, Colorado (JPL Contract No. 954878)	Mullite for container and substrates
Eagle Picher Miami, Oklahoma (JPL Contract No. 954877)	CVD silicon nitride and carbide
RCA Labs Princeton, New Jersey (JPL Contract No. 954901)	CVD silicon nitride
Tylan Torrance, California (JPL Contract No. 954896)	Vitreous carbon

4. Large-Area Silicon Sheet Task Technical Background

a. Shaped Ribbon Technology: EFG Method -- Mobil-Tyco Solar Energy Corp. The edge-defined film-fed growth (EFG) technique is based on feeding molten Si through a slotted die as illustrated in Figure 3-1. In this technique, the shape of the ribbon is determined by the contact of molten Si with the outer edge of the die. The die is constructed from material that is wetted by molten Si (e.g., graphite). Efforts under this contract are directed toward extending the capacity of the EFG process to a speed of 7.5 cm/min and a width of 7.5 cm. In addition to the development of EFG machines and the growing of ribbons, the program includes economic analysis, characterization of the ribbon, production and analysis of solar cells, and theoretical analysis of thermal and stress conditions.

b. Shaped Ribbon Technology: Laser Zone Growth in a Ribbon-to-Ribbon Process -- Motorola. The ribbon-to-ribbon process is basically a float-zone crystal growth method in which the feedstock is a polycrystalline Si ribbon (Figure 3-2). The polysilicon ribbon is fed into a preheated region that is additionally heated by a focused laser beam, melted, and crystallized. The liquid Si is held in place by its own surface tension. The shape of the resulting crystal is defined by the shape of the feedstock and the orientation is determined by that of a seed single-crystal ribbon.

c. Shaped Ribbon Technology -- Westinghouse. Dendritic web is a thin, wide, ribbon form of single crystal silicon. "Dendritic" refers to the two wire-like dendrites on either side of the ribbon, and "web" refers to the silicon sheet that results from the freezing of the liquid film supported by the bounding dendrites. Dendritic web is particularly suited for fabrication into photovoltaic convertors for a number of reasons, including the high efficiency of the cells that can be fabricated from it, the excellent packing factor of the cells into subsequent arrays, and the cost effective conversion of raw silicon into substrates (Figure 3-3).

d. Supported Film Technology -- Honeywell. The purpose of this program is to investigate the technical and economic feasibility of producing solar-cell quality sheet silicon by coating inexpensive ceramic substrates with a thin layer of polycrystalline silicon. The coating methods to be developed are directed toward a minimum-cost process for producing solar cells with a terrestrial conversion efficiency of 12% or greater. By applying a graphite coating to one face of a ceramic substrate, molten silicon can be caused to wet only that graphite-coated face and produce uniform thin layers of large-grain polycrystalline silicon; thus, only a minimal quantity of silicon is consumed.

e. Ingot Technology: Heat Exchanger Method -- Crystal Systems. The Schmid-Vicchnicki technique (heat-exchanger method) has been developed to grow large single-crystal sapphire (Figure 3-4). Heat is removed from the crystal by means of a high-temperature heat exchanger. The heat removal is controlled by the flow of helium gas (the cooling medium) through the heat exchanger. This eliminates the need for motion of the crystal, crucible, or heat zone. In essence

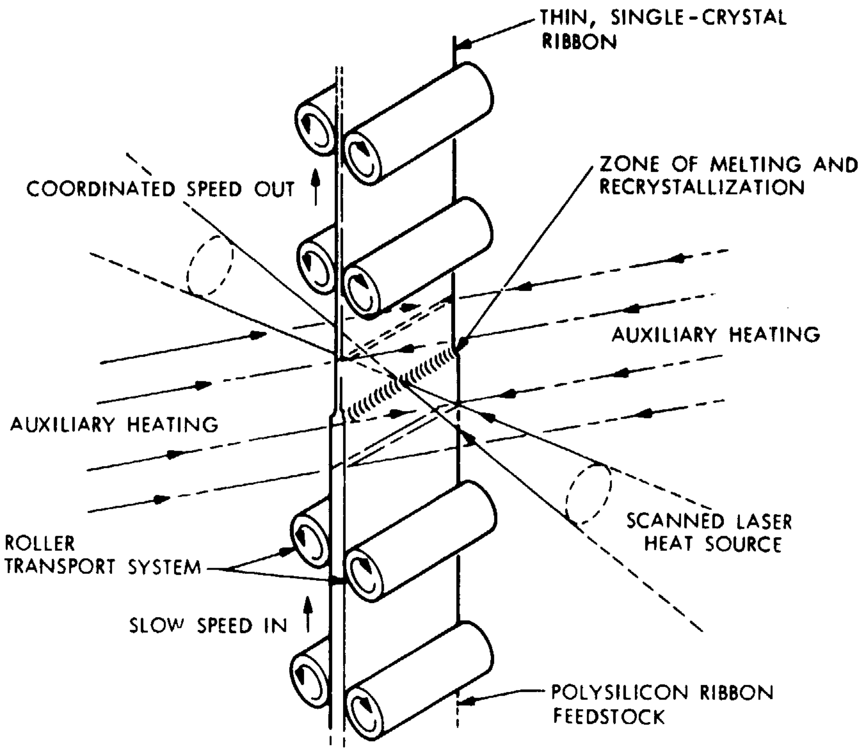


Figure 3-1. Edge-Defined Film-Fed Growth (EFG) -- Mobil-Tyco

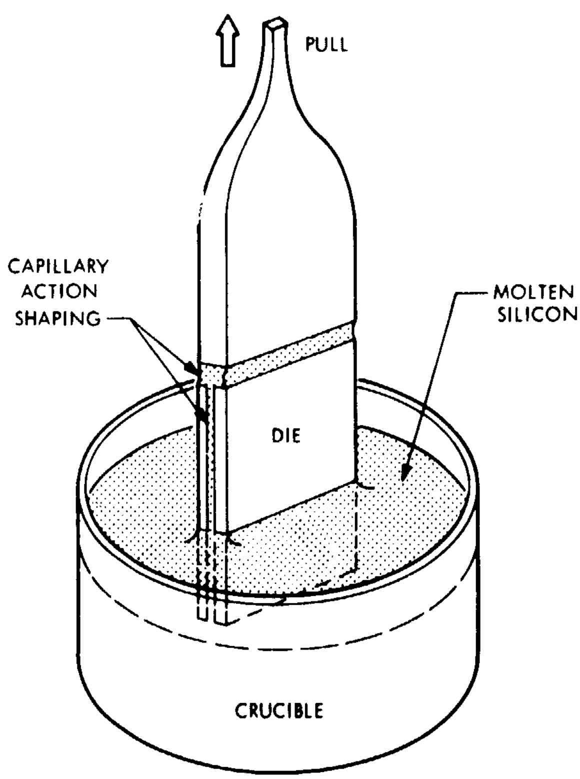


Figure 3-2. Laser Zone Regrowth -- Motorola

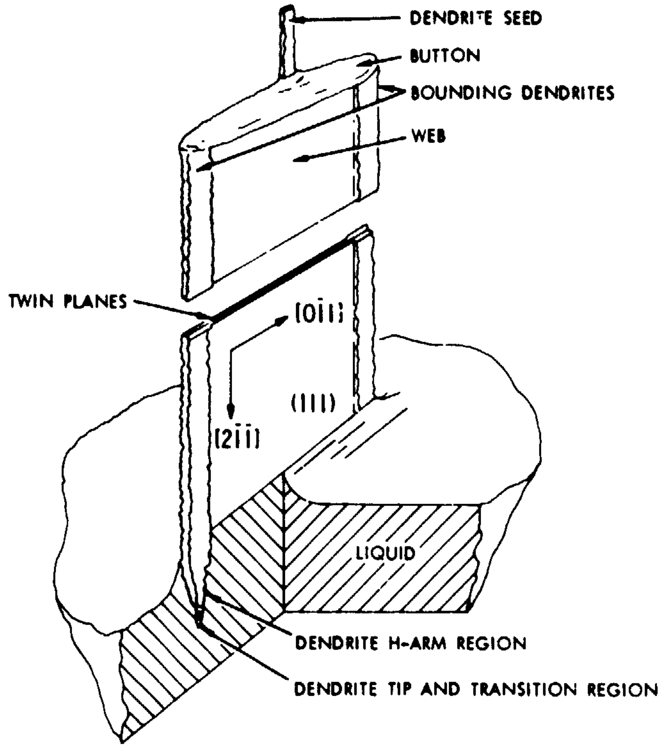
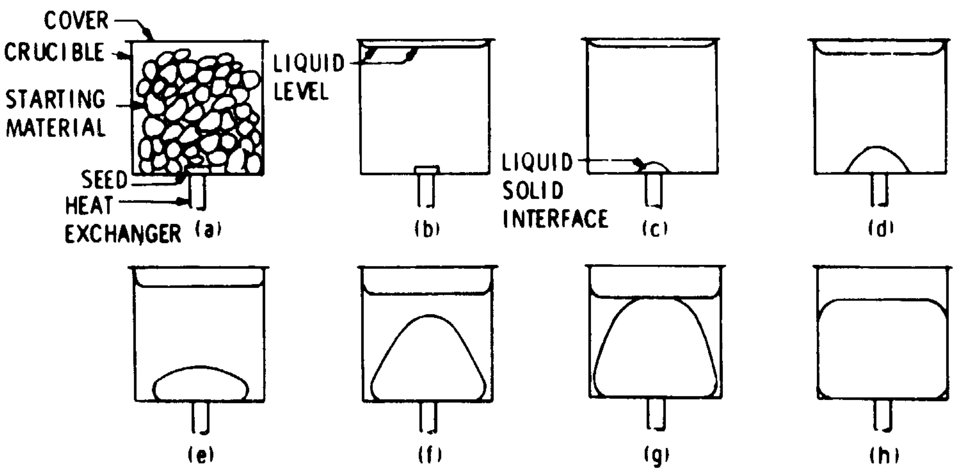


Figure 3-3. Schematic Section of Web Growth -- Westinghouse



Growth of a crystal by the heat exchanger method:
(a) Crucible, cover, starting material, and seed prior to melting.
(b) Starting material melted.
(c) Seed partially melted to insure good nucleation.
(d) Growth of crystal commences.
(e) Growth of crystal covers crucible bottom.
(f) Liquid-solid interface expands in nearly ellipsoidal fashion.
(g) Liquid-solid interface breaks liquid surface.
(h) Crystal growth completed.

Figure 3-4. Crystal Growth Using the Heat Exchanger Method -- Crystal Systems

this method involves directional solidification from the melt where the temperature gradient in the solid might be controlled by the heat exchanger and the gradient in the liquid controlled by the furnace temperature.

The overall goal of this program is to determine if the heat-exchanger ingot casting method can be applied to the growth of large shaped Si crystals (>8 in cube dimensions) in a form suitable for the eventual fabrication of solar cells. This goal is to be accomplished by the transfer of sapphire growth technology (50-lb ingots have already been grown), and theoretical considerations of seeding, crystallization kinetics, fluid dynamics, and heat flow for Si.

f. Ingot Technology: Advanced CZO -- Varian, Texas Instruments, Siltec, and Kayex Corp. In the advanced CZO contracts, efforts are geared toward developing equipment and a process in order to achieve the cost goals and demonstrate the feasibility of continuous CZ solar-grade crystal production (Figure 3-5). Varian will modify an existing furnace for continuous growth using granular silicon for recharging (molten silicon will also be considered), and a new puller is to be designed. Texas Instruments' technique is based on an incoming flow of solid granular or nugget polysilicon, premelted in a small auxiliary crucible from which liquid silicon will be introduced into the primary crucible. Siltec's approach is to develop a furnace with continuous liquid replenishment of the growth crucible accomplished by a meltdown system and a liquid transfer mechanism with associated automatic feedback controls. Kayex will demonstrate the growth of 100 kg of single crystal material using only one crucible by perodic melt replenishment.

g. Ingot Technology: Multiwire Sawing -- Crystal Systems; Multiblade Sawing -- Varian. Today most Si is sliced into wafers with an inside diameter saw, one wafer at a time being cut from the crystal. This is a large cost factor in producing solar cells. The multiblade and multiwire slicing operations employ similar reciprocating blade head motion with a fixed workpiece. Multiblade slicing is accomplished with a slurry suspension of cutting fluid and silicon carbide abrasive and tensioned steel blades of 6 mm height and 0.2 mm thickness. Multiwire slicing uses 0.5 mm steel wires surrounded by a 0.25 mm copper sheet, which is impregnated with diamond as an abrasive.

h. Contact Material -- Battelle Labs, Coors Porcelain, Eagle Picher, RCA Labs, and Tylan. In the crystal-growing processes, a refractory crucible is required to hold the molten silicon, while in the ribbon processes an additional refractory shaping die is needed. The objective of these contracts is to develop and evaluate cost effective refractory die and container materials. The material must be mechanically stable to temperatures above the melting point of silicon, must not excessively contaminate the silicon processed through it, be amenable to the fabrication of dies and containers with close tolerances and of varying geometries, and be cost effective. Two of the contracts in this area, RCA and Tylan, are to develop a substrate material for supported film growth and a coating for substrates, dies, and containers.

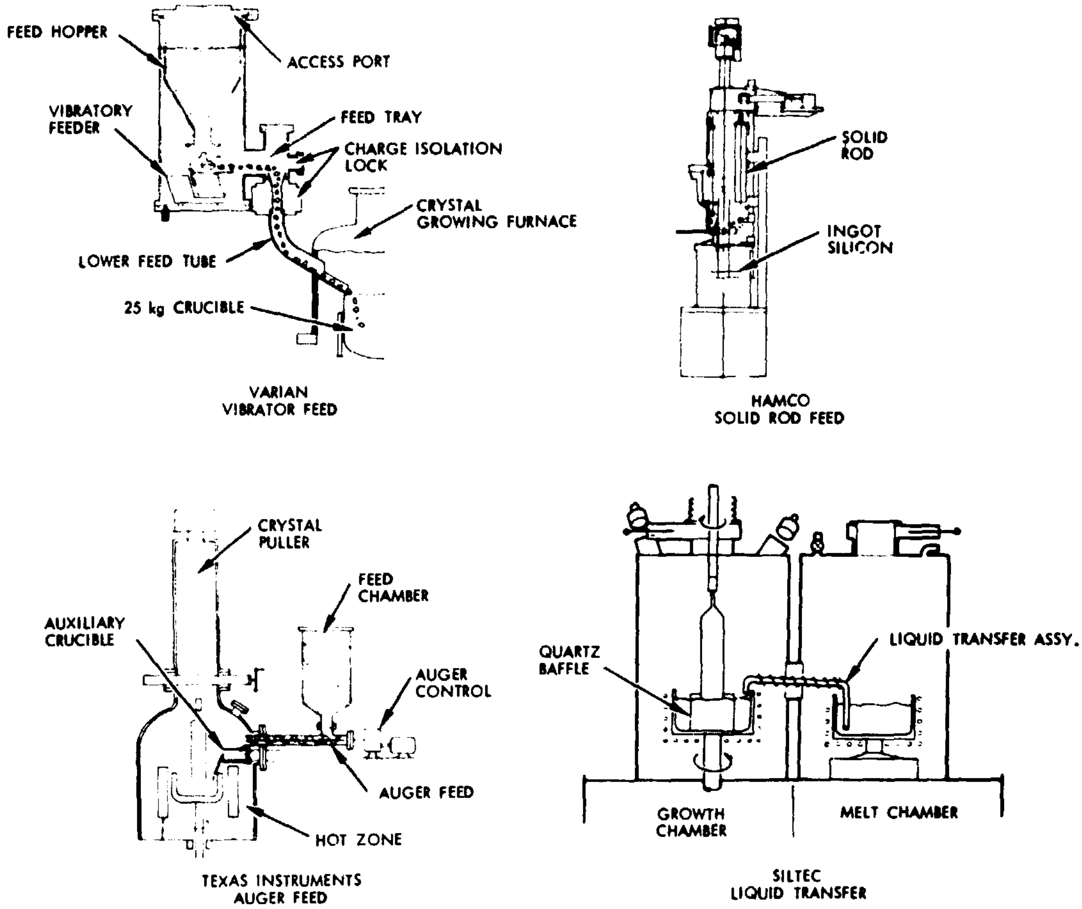


Figure 3-5. Continuous CZ Crystal Growth Machines

5. Summary of Progress

a. Shaped Ribbon Technology. At Mobil Tyco, the main emphasis this quarter was on production and evaluation of a series of baseline "clean runs" designed to demonstrate that the furnace, when operating without any stainless steel parts in the interior, could produce material of a chemical quality sufficient to prepare solar cells of ∿10% efficiency. Motorola achieved a growth rate of 38 cm^2/min using CVD feedstock, both with a 7.6 cm wide ribbon grown at 5 cm/min and with a 5 cm wide ribbon grown at 7.6 cm/min.

b. Supported Film Technology. Coors and Honeywell are both processing slotted substrates of various configurations. These have been dipped and processed into cells. Excellent dip coatings were obtained on substrates with slot widths of 0.5 cm spaced on 1-mm centers. The SCIM coater runs made during this quarter were unsuccessful in providing uniform silicon coatings. RCA Labs accomplished epitaxial growth on "upgraded metallurigical grade" silicon. Cells fabricated into 15 μm thick epitaxial layers grown on this material resulted in AM-1 efficiencies ranging from 12% to 13% compared with only 4% to 5% when cells were made by direct diffusion.

c. Ingot Technology. Crystal Systems achieved a high degree of crystallinity in the square ingots cast. High purity square crucibles are being fabricated. Efficient slicing was carried out with 30 μm and 22 μm diamonds in addition to the 45 μm size. The use of synthetic diamonds gave a poorer performance when compared with the natural kind. Developments in the advanced Czochralski process are as follows: Kayex Corp. -- Two recharges (three melts and ingot growth cycles from the same crucible) have been demonstrated and 42.5 kg of single crystal material have been pulled from one crucible by melting a total of 48.7 kg in three successive melts. Siltec Corp. -- Furnace design was completed, and is in the fabrication stage. An experiment was performed with a standard production furnace to demonstrate controlled flow of molten silicon through a small ID tube by pressure differential. Varian (CZO) -- Five crystals were grown with a total throughput of 48 kg. The design of the prototype Czochralski puller was begun on schedule. Two critical components have already undergone advance trials, the recharging mechanism and crystal life mechanism. Varian (MBS) -- Looser tolerance blades were tested with results that indicate that cheaper blades may be useful. The lab saw was tested and performs well. A "bounce fixture" that reduces end-of-stroke shock leads has shown significant improvements. The prototype large saw was tested and first run gave 88% yield; loss of wafers occurred mostly during cleaning.

d. Contact Material. Initial studies by Battelle Labs have shown that β' Sialon appears to offer some promise as a candidate die material.

Coors Porcelain has found that a mixture of fused mullite and fused silica fires to a body with thermal expansion very near that of silicon. At Eagle Picher, initial sessile drop experiments on SiC, Si_3N_4, and AlN have been conducted. Promising results have been achieved on both SiC and Si_3N_4. Hot pressing experiments have begun on crucible shapes and characterization efforts have also begun on coatings and substrates. RCA Labs, using X-ray analysis, has studied the thermal stability of CVD SiO_xN_y layers in contact with molten silicon. The results indicate that these layers are converted to the α and β phases of Si_3N_4 with the β phase predominating.

C. ENCAPSULATION TASK

The objective of the Encapsulation Task is to develop and qualify a solar array module encapsulation system that has a demonstrated high reliability and a 20-year lifetime expectancy in terrestrial environments, and is compatible with the low-cost objectives of the Project.

The scope of the Encapsulation Task includes developing the total system required to protect the optically and electrically active elements of the array from the degrading effects of terrestrial environments. The most difficult technical problem is expected to be developing the element of the encapsulation system for the sunlit side; this element must maintain high transparency for the 20-year lifetime, while also providing protection from adverse environments.

In addition, significant technical problems are anticipated at interfaces between the parts of the encapsulation system, between the encapsulation system and the active array elements, and at points where the encapsulation system is penetrated for external electrical connections. Selection of the element for the rear side (i.e., the side opposite to the sunlit side) of the encapsulation system will be based primarily on cost, functional requirements, and compatibility with the other parts of the encapsulation system and with the solar cells.

Depending on the final solar array design implementation, the encapsulation system may also serve other functions, e.g., structural, electrical, etc., in addition to providing the essential protection.

At present, options are being kept open as to what form the transparent element of the encapsulation system will take -- glass or polymer sheet, polymer film, sprayable polymer, castable polymer, etc. The transparent element may contain more than one material and may be integral with the photovoltaic device, or be bonded to it.

1. Organization and Coordination

The approach being used to achieve the overall objective of the Encapsulation Task includes an appropriate combination of contractor and JPL in-house efforts. The contractor efforts will be carried out in two phases. Within each phase some parallel investigations are being conducted to assure timely accomplishment of objectives.

During Phase I the contractor efforts and the JPL in-house efforts consisted primarily of a systematic assessment and documentation of the following items:

(a) Potential candidate encapsulant materials based on past experience with the encapsulation of Si and other semiconductor devices, and on available information on the properties and stability of other potential encapsulant materials and processes.

(b) The environment that the encapsulation system must withstand.

(c) The properties, environmental stability, and potential improvement of potential encapsulant materials and processes.

(d) Test and analytical methods required to evaluate performance and predict and/or verify lifetime of encapsulant materials and encapsulation systems.

The result of this effort will be used to specifically define additional research, development, and evaluation required during the subsequent phase.

Throughout the task atypical or unique approaches to solving the encapsulation system problem will be sought and evaluated. For

example, Phase I includes an evaluation of the feasibility of utilizing electrostatically-bonded integral glass covers as part of the encapsulation system.

In Phase II, contractor and JPL in-house efforts will be conducted to identify and/or develop one or more potentially suitable encapsulated systems and then verify the expected lifetime and reliability of these systems. Depending on the results of Phase I, the contractor effort in this phase will include an appropriate combination of some of the following items:

(a) Evaluate, develop, and/or modify solar module testing and analytical methods and then validate these methods.

(b) Perform materials and interaction testing, using these methods to evaluate candidates and demonstrate the reliability of encapsulation systems.

(c) Modify materials and processes used in encapsulation systems to improve automation and cost potential.

(d) Modify potential encapsulation system materials to optimize mechanical, thermal, and aging properties.

(e) Implement research and development on new encapsulant materials.

2. Encapsulation Task Contracts

Encapsulation Task contracts are shown in Table 3-4. In addition, Professor Charles Rogers, Department of Macromolecular Science, Case Western Reserve University, serves as a consultant to this task (JPL Contract No. 954738) and will also implement selected supporting experimental investigations in the laboratories at Case.

Contractual efforts in the coming months include follow-on contracts to four major contractors, a contract with the Rockwell Science Center to study the interface characteristics of encapsulated solar cells, a contract with the Motorola Solar Energy Department to develop antireflectance coatings for glass, a contract with Endurex of Mesquite, Texas, to continue the study of ion-plating coating techniques, and a contract with Battelle to develop a life prediction testing plan for solar arrays at a specific deployment site.

3. Encapsulation Task Technical Approach

Program efforts to date have provided an assessment of the state of the art and a definition of the potential environmental and operational stresses imposed on the encapsulation system. A data base on candidate materials and their responses to these stresses is being accumulated and analyzed. Technology deficiencies are being experimentally exposed and documented.

Table 3-4. Encapsulation Task Contractors

Contractor	Technology Area
Battelle Labs Columbus, Ohio (JPL Contract No. 954328)	Measurement techniques and instruments for life prediction testing
Case Western University Cleveland, Ohio (JPL Contract No. 954738)	System studies of basic aging and diffusion
Dow Corning Corp. Midland, Michigan (JPL Contract No. 954995)	Develop silicone encapsulation systems for terrestrial silicon solar arrays
Endurex Corp. Dallas, Texas (JPL Contract No. 954728)	Ion-plating process and testing
Rockwell International Anaheim, California (JPL Contract No. 954458)	Test methods and aging mechanisms
Rockwell Science Center Thousand Oaks, California (JPL Contract No. 954739)	Materials interface problem study
SPIRE Corp. Bedford, Massachusetts (JPL Contract No. 954521)	Electrostatic bonding process
Springborn Labs, Inc. Enfield, Connecticut (JPL Contract No. 954527)	Encapsulation test methods and materials properties evaluation

4. Summary of Progress

An add-on to the Springborn contract was executed. A program plan prepared by Springborn was reviewed by JPL and approved with some mutually agreed upon modifications. A final version of Springborn's second annual report was agreed to; it will be distributed shortly.

A program plan representing joint ITW/Endurex involvement was received, evaluated, and approved. ITW began to use its technology to apply and evaluate ion-plated coatings. In addition, Endurex began work on ion-plated metallization utilizing ITW corrosion-resistant alloys.

An add-on to the Battelle contract was executed to do a life prediction study on the photovoltaic modules in field test by Lincoln Laboratory/University of Nebraska near Mead, Nebraska. A meeting was held among representatives from Battelle, JPL, and Lincoln Laboratories to establish a cooperative effort.

The Battelle final report draft, "Evaluation of Encapsulation Methods and Materials for Low-Cost Long-Life Silicon Photovoltaic Arrays," was approved by JPL.

The Motorola final report, DOE-JPL-954773-78/1, "Studies and Testing of Antireflective Coatings for Soda-Lime Glass," was distributed.

All planned modifications to the electrostatic bonder at SPIRE have been completed. Work was started on defining optimum materials and processes. Work was started by the University of Maine under subcontract to SPIRE to investigate the physics of electrostatic bonding of metals to glass.

The final report draft was received from Rockwell Autonetics and is being reviewed by JPL.

An amended version of Dow Corning's Phase I program plan was approved and experimental activities initiated. First efforts are to identify silicones which have undergone outdoor weathering for up to 20 years.

An in-house effort was begun to study the processing of polymers in the various encapsulation systems being tested at JPL and by Encapsulation Task contractors.

The Rockwell Science Center annual report was received. The Discussion of Results includes a discussion of a relatively new methodology termed Preventive Nondestructive Evaluation (PNDE) and its adaptation to LSA applications.

SECTION IV

PRODUCTION PROCESS AND EQUIPMENT AREA

The objective of the Production Process and Equipment Area is to identify, develop, and demonstrate energy-conservative, economical processes for the fabrication of solar cells and arrays at a production price of less than $500 per peak kilowatt. The schedule is shown in Figure 4-1.

The Production Process and Equipment Area effort is now in Phase II, Process Development. A milestone chart with the major milestones identified is contained in Figure 4-2. Phase II, initiated in September 1977, is well under way at this time. Processes are being developed in the four major areas of fabrication; that is, surface preparation, junction formation, metallization, and assembly. The contractors involved in these efforts are shown in Table 4-1.

During the 9th Project Integration Meeting, a tutorial presentation was given by SPIRE Corporation. Figure 4-3 shows the interrelationship between the fluence and the depth for varying electron voltages used in the implant. Figure 4-4 indicates the depth at which a fluence of $5 \times 10^{15}/m^2$ of phosphorus occurs when the implantation is done through a native oxide of varying thicknesses. Figure 4-5 depicts the thermal decay as generated by the computer model for varying periods of time after the initial pulse for electron beam annealing. Figure 4-6 shows in pictorial form the result of varying dosage levels on the silicon crystal substrate.

A. SURFACE PREPARATION

Layers of titanium dioxide for AR coating applications have been produced by pulling from a liquid metal-organic precursor at speeds up to 40 ft/min. This is using a low solids content (approximately 0.5% by weight of TiO_2). Texture etching technology advancement has occurred in the area of creation of smaller peaks to reduce the physical damage occurring in subsequent handling. In addition, more uniformly sized peaks are created. In-house production of spray-on AR coating solutions has resulted in both a substantial cost savings and much better control over the concentrations. Spray-on AR coatings yielding films of titanium dioxide with a refractive index of 2.1 were attained by use of a Zicon Model 1100 Autocoater.

B. JUNCTION FORMATION

A Silox reactor for doped oxides processing used in the formation of backsurface field regions has given results comparable to those achieved with a cold-wall open-tube reactor. In addition to this, the Silox reactor becomes less expensive because it is more conservative of materials, and it is better suited to the processing of continuous ribbons of webbed silicon. Titanium impurities up through 500 ppma were deliberately implanted through doping of reagent-grade phosphorus

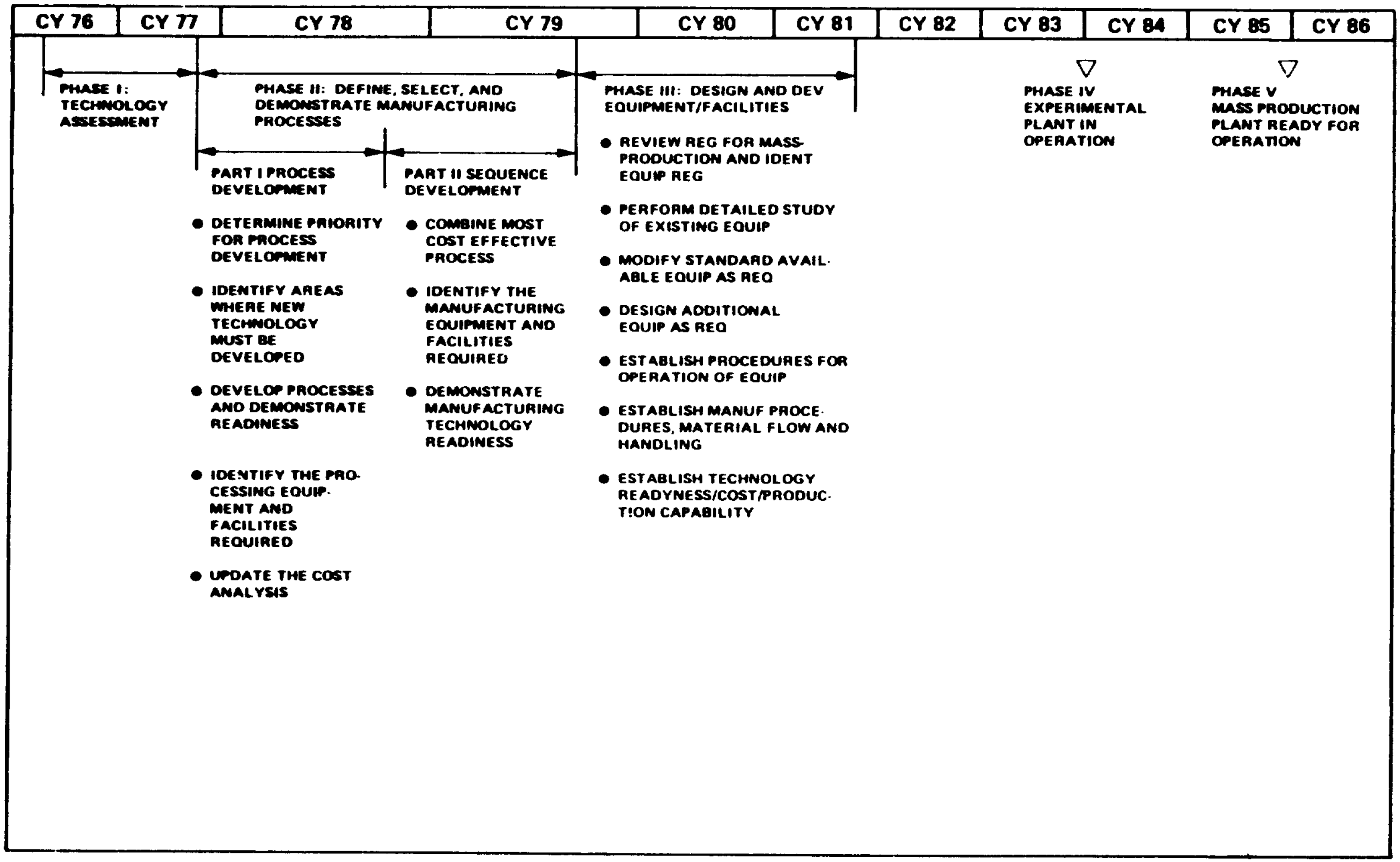


Figure 4-1. Production Process and Equipment Area Schedule

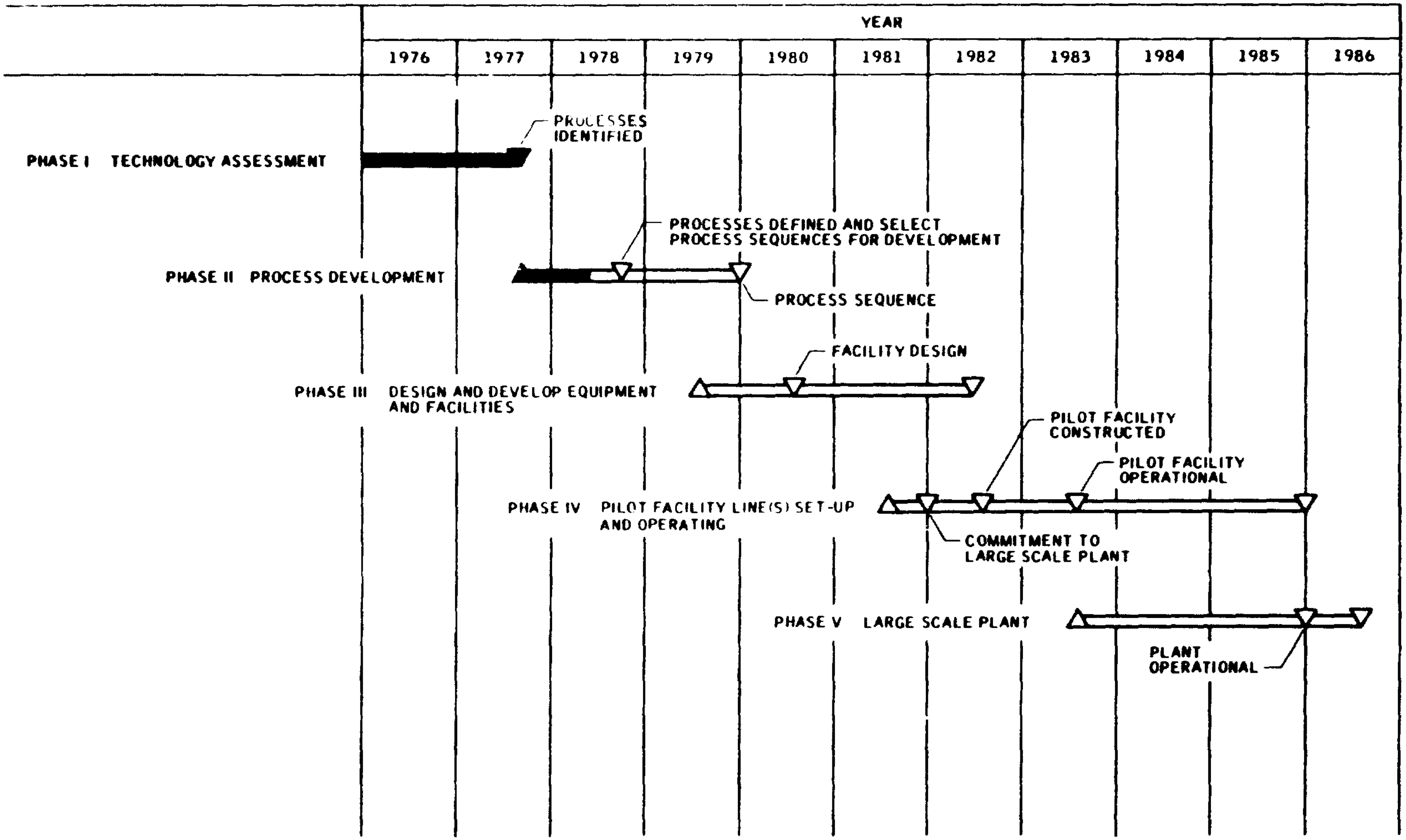


Figure 4-2. Production Process and Equipment Area Major Milestones

Table 4-1. Production Process and Equipment Area Contractors

Contractor	Type Contract	Technology Area
General Electric R&D Philadelphia, Pennsylvania (JPL Contract No. 954607)		Shingle type modules
Kinetic Coatings, Inc. Burlington, Massachusetts (JPL Contract No. 955079)		Ion implantation
Lockheed, Inc. Sunnyvale, California (JPL Contract No. 954410)		Spraylon
Lockheed, Inc. Sunnyvale, California (JPL Contract No. 954898)	Phase II	Process development
Mobil Tyco Solar Waltham, Massachusetts (JPL Contract No. 954999)		Developmental solar modules
MBA San Ramon, California (JPL Contract No. 954882)	Phase II	Process development
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954363)		Technology assessment
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954689)		Metallization of Si wafers
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954716)		Parallel oriented interconnects
Motorola, Inc. Phoenix, Arizona (JPL Contract No. 954847)	Phase II	Process development
Optical Coating Lab City of Industry, California (JPL Contract No. 954831)		High efficiency, long-life solar panels
Optical Coating Lab City of Industry, California (JPL Contract No. 954830)		Slicing

Table 4-1. Production Process and Equipment Area Contractors (Continuation 1)

Contractor	Type Contract	Technology Area
Optical Coating Lab City of Industry, California (JPL Contract No. 955118)		Ion implanter invest.
RCA Corp. Princeton, New Jersey (JPL Contract No. 954868)	Phase II	Process development
Sensor Technology Chatsworth, California (JPL Contract No. 954605)		High efficiency panels
Sensor Technology Chatsworth, California (JPL Contract No. 954865)	Phase II	Production process sequence
Solarex Corp. Rockville, Maryland (JPL Contract No. 954822)		High density panels
Solarex Corp. Rockville, Maryland (JPL Contract No. 954854)	Phase II	Process development
Solarex Corp. Rockville, Maryland (JPL Contract No. 955077)		Wafer thickness evaluation
Spectrolab, Inc. Sylmar, California (JPL Contract No. 954853)	Phase II	Process development
SPIRE Corp. Bedford, Massachusetts (JPL Contract No. 954786)		Ion implanter
Texas Instruments Dallas, Texas (JPL Contract No. 954881)	Phase II	Process development
University of Pennsylvania Philadelphia, Pennsylvania (JPL Contract No. 954796)		Automated array
Westinghouse Research Pittsburgh, Pennsylvania (JPL Contract No. 954873)	Phase II	Process development

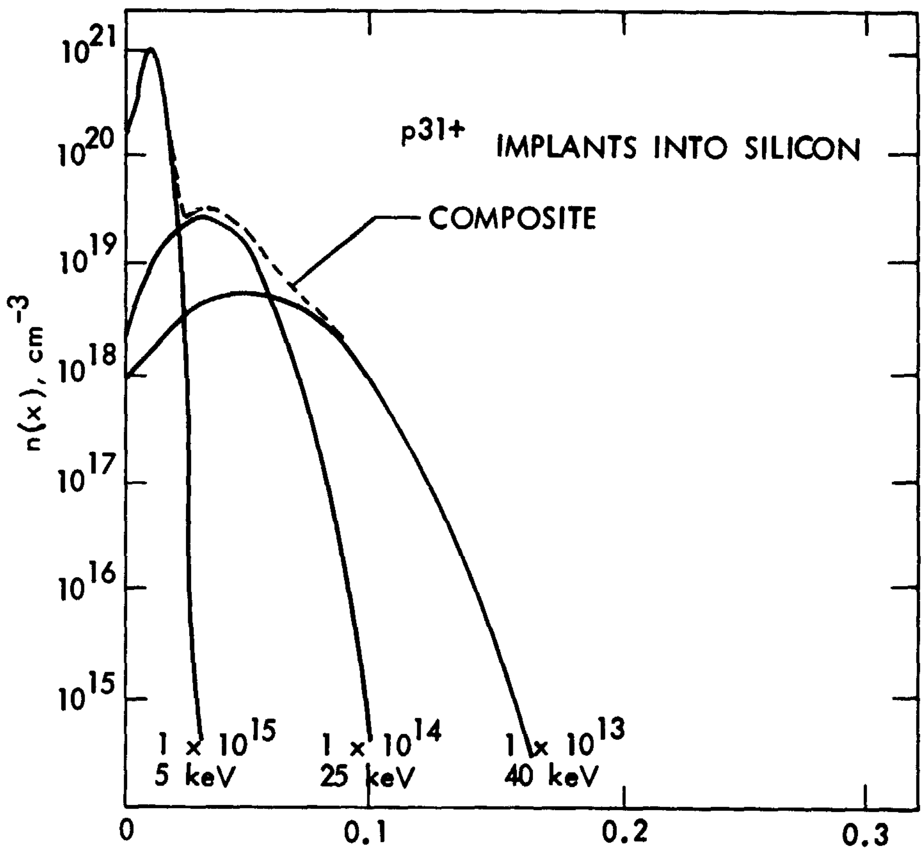


Figure 4-3. Interrelationship Between Fluence and Depth for Varying Electron Voltages

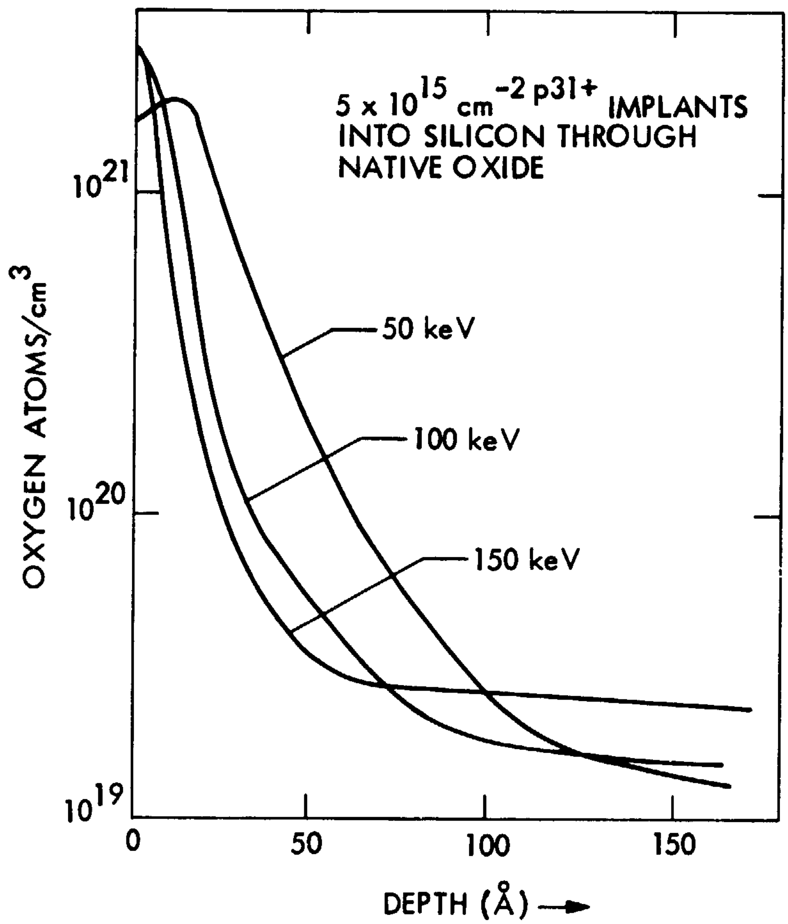


Figure 4-4. Depth at Which Fluence of $5 \times 10^{15}/m^2$ of Phosphorous Occurs

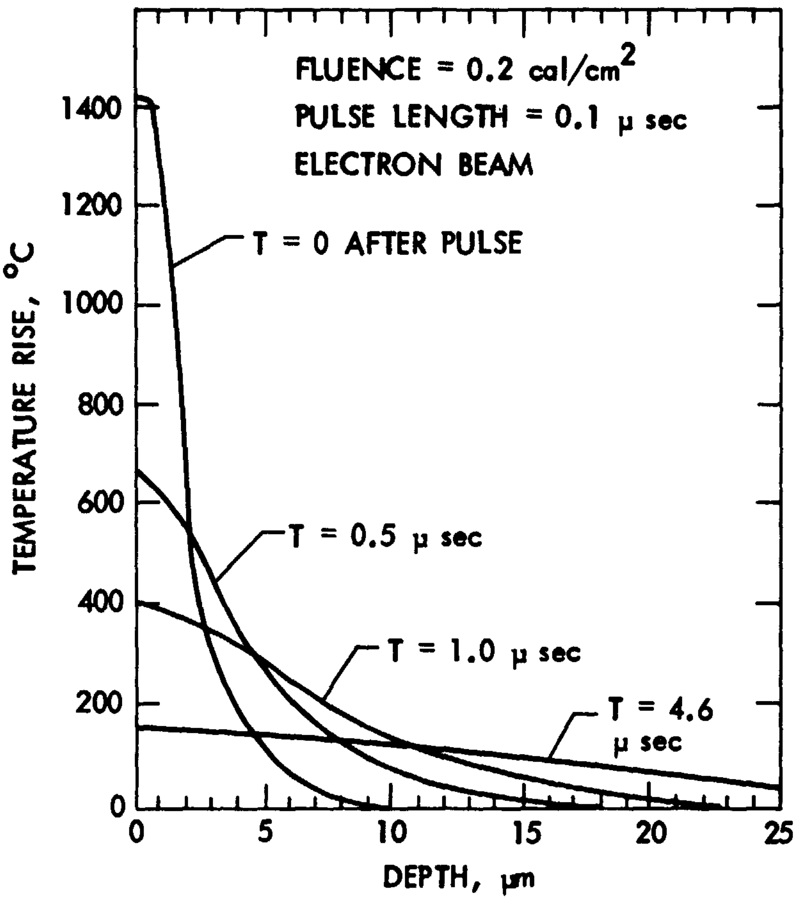


Figure 4-5. Thermal Decay as Generated by Computer Model

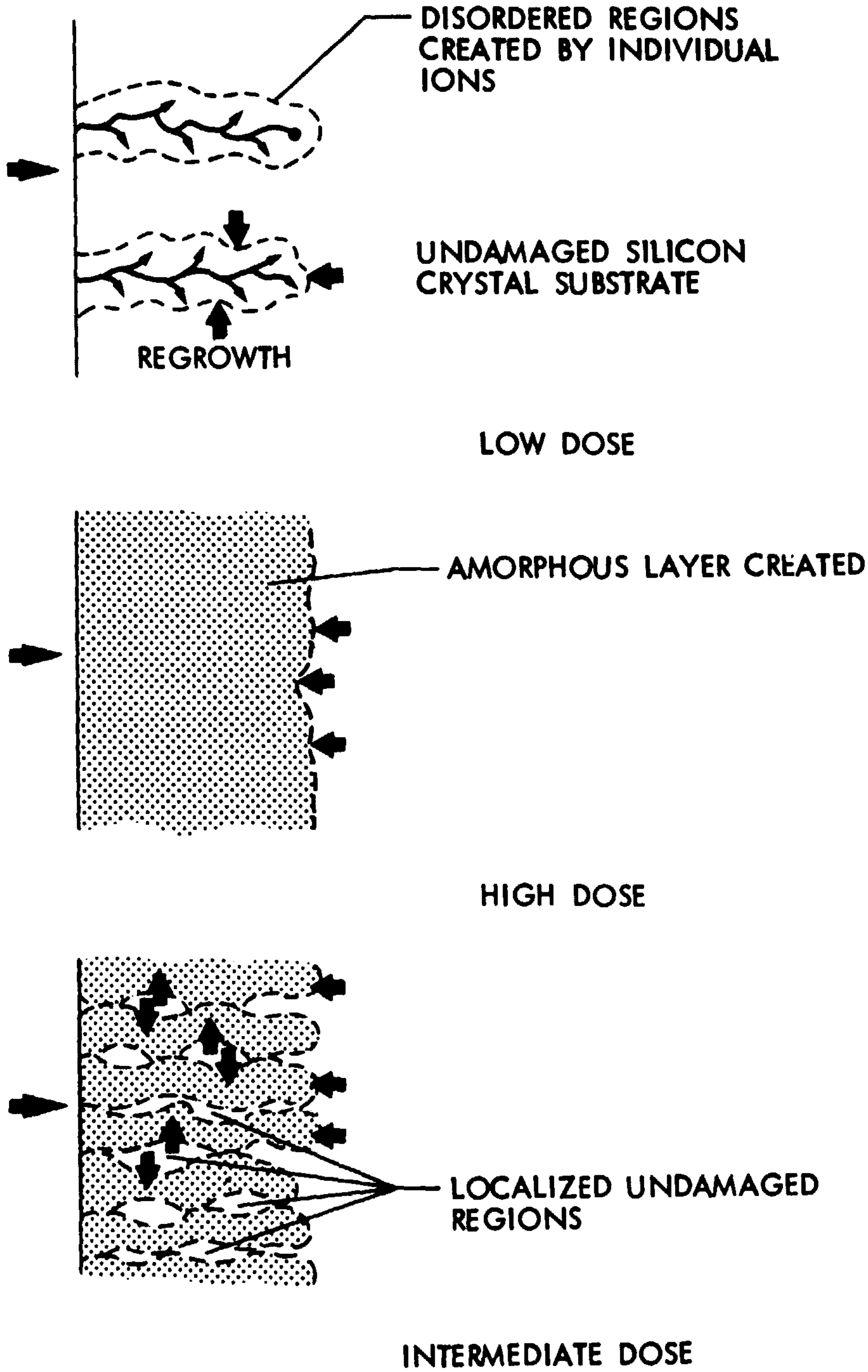


Figure 4-6. Result of Varying Dosage Levels on Silicon Crystal Substrate

oxychloride. After the doping and diffusion occurred, the glasses resulting from the diffusion were analyzed using secondary ion mass spectroscopy and they showed lower ratios of titanium concentration than established in the phosphorus oxychloride. It is postulated that differences in vapor pressure of the two chlorides (since titanium tetrachloride was used), and differences in the oxidation mechanisms for the phosphorus and titanium, actually reduced the amount of titanium incorporated in the glass. The implication for reduced costs in cell manufacturing is that concentrations of below 500 ppma titanium contained within the reagent-grade phosphorus oxychloride can be allowed, and consequently the cost of procurement of the $POCl_3$ should be lessened.

It was ascertained by one contractor that arsenic spin-on polymer dopants were not cost effective due to the high process temperatures and long diffusion times required. It was determined that phosphorus spin-on at 850°C gave the best results and it has been verified that in the ion implantation the peak in cell performance occurred at a fluence of 5×10^{15} atoms/cm^2 of phosphorus.

The use of spray-on dopants has, in preliminary tests, shown very good results. It has been shown that dopants can be sprayed on without wafer edge overlap and with good dopant uniformity.

C. METALLIZATION

It has been shown that metallization of silicon wafers can be efficiently done with negative silk-screening, electroless nickel-plating, and wave soldering. In addition, it is postulated that this process sequence will lend itself very well to automation and therefore be very cost effective. Various mechanical and environmental tests performed on cells fabricated with this sequence have all indicated that the sequence is in no manner degrading to the cell. It was found after review that wax masking is better done with a melted wax technology than a solvent system. Another contractor has shown that both in-house formulated and commercially-available thick film inks readily can be used with various firing methods, including belt furnace and infrared lamp heating. Penetration studies conducted by a surface damage inspection have verified this. Tests pertaining to solder adhesion and electrical performance have also shown positive results.

D. ASSEMBLY

Ultrasonic seam bonding of foil interconnects to the cell metallization has been postulated as a potentially higher throughput, lower cost method of interconnection. Work in this area is being pursued. Another contractor has been studying the potential for automated array assembly by using an industrial robot. The advantage that appears to be gained by this approach is that many programs can be performed by the same robot by simply changing the program card. An attempt is being made to identify and obtain the best robot for this purpose. Condensation of vapor phase reflow soldering has been shown to be the

best process at one contractor. Arc spraying of interconnects on solar cells has been shown to be both cost effective and easily performed. A variety of materials are being investigated as well as another method of interconnection utilizing radiant heating: a one-foot-square prototype was constructed in a single pass and several nine-cell solar arrays were produced. The technique shows promise for mass production capability within a short period of time. A system for trimming into a hexagonal shape and placing a hole in the center of the solar cell for face connections has been shown to be an excellent method, with the drawback that the utility costs are currently quite high and the interconnect system is currently expensive. Efforts are being put forth to reduce the costs on both of these.

E. ADVANCED MODULE DEVELOPMENT

Test results on shingle modules have, to this point, been encouraging. The modules, manufactured by OCLI, have the performance characteristics shown in Table 4-2 (as reported by OCLI).

Table 4-2. Shingle Module Performance

ELECTRICAL PERFORMANCE
(At 100 mW/cm^2 and 28^{o}C)

MODULE NO.	I_{sc} (A)	V_{oc} (mV)	P (W)	EFF. (%)
1	6.083	190.89	87.73	12.6
2	6.241	190.38	88.99	13.0
3	6.360	190.65	88.99	13.0
4	6.124	190.65	89.96	13.2
5	6.321	189.45	89.80	13.2
6	6.261	189.45	89.23	13.1

SECTION V

ENGINEERING AREA

During the quarter the Engineering Area has continued activities in the areas of array design guidelines, reliability-durability requirements, and array specifications and standards.

In the area of design guidelines, the Bechtel and Boeing contracts completed the analytical portions of the module requirements studies and preparation was initiated of draft final reports for both contracts. Following review of proposals submitted in response to the Residential Module Requirements Study RFP, Burt, Hill, Kosar, Rittleman Associates (Butler, Pennsylvania) was selected for negotiation of the study contract with work to begin in early July. Work on application of non-linear structural analysis to support module structural design continued this quarter. The effort was centered on the use of three different large computer programs -- ANSYS, MARC, and ARGUS -- to develop non-dimensional sizing criteria for uniformly-loaded, simply supported rectangular plates. Lack of agreement between the programs has been finally resolved and a handbook type report on module structural sizing is in preparation. Effort was also spent this quarter modifying the computer program used to determine series/parallel combinations of cells and modules, to provide for multiple failures in a non-varying sequence. The program has been restructured to make it more efficient in cases involving large numbers of cells and modules. Estimates were also made during the quarter of the total material required for manufacturing and installing solar arrays sufficient to generate 4 quads (10^{15} Btu) of energy per year. This is equivalent to about half of the total production of electricity in the U.S. today. Assuming an installation rate of 100,000 MWe/year (1/2 quad/year), the material requirements for support structures approach the present national production of resources such as cement, sand and gravel, aluminum, steel, and glass. These results place additional emphasis on reducing support structure requirements.

In the area of reliability-durability requirements, the final group of hail tests of Block III and advanced module designs was completed. More than one survived 2-in ice ball impacts at 116 ft/s. The second phase of the module bias-humidity testing using Block II minimodules was completed and only limited bias-related changes were observed. Preparation of a final report documenting the results was initiated. In the environmental test development task, surface soiling exploratory tests were conducted by dispersing a standard air filter test dust on Block II minimodules and inverting the modules to remove loosely adhered particles. Although the results confirm the greater susceptibility of silicone rubber encapsulants over glass covers for dust accumulation, the data did not correlate well with field experience. Alternative testing methods are under investigation, including selective dispersal techniques and possible design of a particulate deposition chamber. The results of the first quarter work on the Clemson University cell reliability contract was distributed to the photovoltaic community. Phase I testing was 80%

completed and cell performance measurement capability was upgraded with repeatable measurements within 0.2% demonstrated. A contract was negotiated with DSET Laboratories, Inc. (Phoenix, Arizona) to continue accelerated (8X) sunlight aging exposure of Block II mini-modules on the large-scale Super-MAQ through the end of FY'78, as initiated jointly by JPL and Lewis Research Center in FY'77. DSET personnel inspect the samples weekly and perform I-V tests monthly.

In the area of specifications and standards, a new module design requirement, document 5101-65 (DOE/JPL-1012-78/7), "Photovoltaic Module Design, Qualification and Testing Specifications," dated March 24, 1978, has been released for distribution to the photovoltaic community. This specification applies to 20 kW to 500 kW installations as typified by the applications defined in PRDA EM-D-04-0038. A major effort was made during this quarter to examine various photovoltaic definitions and design criteria and recommend a preferred set for common use by both flat-plate and concentrator technologies. The concepts were factored into the overall SERI photovoltaic standards effort at a meeting of the SERI advisory committee held at JPL on April 10, 11. Other outside interfaces during the quarter included attending and making several presentations at the 9th PIM, attending and presenting three papers at the Institute of Environmental Sciences (IES) National Conference in Fort Worth, participation in several quarterly contract reviews at Sandia, participation in the SERI-led subcommittee meetings on photovoltaic standards at Vail, Colorado, and presentation of two papers at the 13th IEEE PV Specialists Conference.

SECTION VI

OPERATIONS AREA

A. SUMMARY OF PROGRESS

1. Large-Scale Production Task

a. Block III. All contractors delivered modules in this quarter. Start-up problems were evident. Although a total of 36 kW of modules were delivered, this quantity was only 35% of the amount projected by the contractors at the beginning of the quarter. The failure to perform as planned seems largely to be a result of under estimating the quality assurance requirements for production.

The Solarex high-efficiency module was produced in sufficiently large quantities to power Sun Day and Photovoltaic Specialist Conference exhibits, although the efficiency of the delivered modules at 60°C was closer to 8% rather than the 10% originally projected by Solarex.

b. Block IV. A draft of the RFP for the design, development and limited production of the "third generation" module approached completion during this quarter.

2. Environmental Testing

a. Large-Scale Production (Task 5) Modules

1) Block II. The only activity with these modules was a final exploratory humidity-heat test on three Type W modules. No degradation was observed.

No further testing is planned on Block II modules. A final report is in preparation.

2) Block III. Four Type Y and five U modules completed and passed the standard temperature cycling, humidity, and pressure cycling (wind simulation) test series. The U modules were the initial qualification set; the Y modules were the first set of production samples. The only observed degradation was some darkening of the cell collectors on the Y modules and slight delamination near two cells of one of these modules.

Another set of U modules, designed for military use, was procured by Engineering and quality tested. The foil interconnector material wrinkled slightly in temperature cycling. One of the five modules showed some delamination at the cells after humidity and another had modest electrical degradation after pressure cycling.

Five vendor sets of 10 modules were tested for temperature coefficients this quarter. They were Types U, U(Military), V, YH (Y-high density), and Z.

After measurement of temperature coefficients, about 25 each of module Types U, V, Y, and Z were electrically tested to verify the vendors' power measurements.

b. Automated Array Assembly (Task 4) Developmental Modules. The below listed environmental tests were performed this quarter:

Manufacturer	Quantity	Tests Performed
O	4	Full qualification
YH	6	Full qualification
K	4	Temperature and humidity cycling
M	2	Full qualification

The Type O module is a 29 x 58 cm assembly with aluminum extrusion substrate, silicone gel encapsulant, and a glass cover. Each of the 43 cells is series-wired via a stud passing through a hole in the center of the cell. Two of the four modules tested failed the temperature cycling test, one with a cracked cover glass and an open circuit and the second with 21% electrical degradation. All four had many air bubbles form over the cells. No further degradation was noted after humidity and pressure cycling.

The YH module comprises two 35-cell series strings of 5 x 5 cm square cells on a polyester substrate supported with an aluminum frame. Sylgard 184 encapsulates the cells. Overall dimensions are 38 x 51 cm. All six modules tested passed temperature and humidity cycling. During pressure cycling, two modules developed one cell crack each, another had 5% electrical degradation, and one had mild encapsulant delamination.

The Type K module is basically a hexagon, 24 cm across the flats, containing 19 series-connected 53 mm diameter solar cells. The semiflexible substrate is a laminate, with Hypalon core, with a rectangular flap such that these modules can be "shingled" to produce a nested array of hexagons. The encapsulant is polyvinyl butyral, and a tempered glass cover is used. After temperature cycling, one of the modules tested had a severely cracked cover glass, five cracked cells, and 75% electrical degradation. The Hypalon material was warped on all modules and in three cases was blistered also. One terminal dropped off the back side on one. The three best modules were then tested in humidity. One cell of one module cracked.

The Type M module has eight parallel 32-cell strings of 3.7 x 7 cm rectangular cells, which are overlapped to eliminate the spacing between cells. The substrate is aluminum, the encapsulant is RTV 602, and a cover glass is provided. Overall module dimensions are 59 x 117 cm. Two modules were tested in temperature cycling at a contractor's facility in San Diego without any visual damage noted by the technicians there. On arrival at Pasadena, one module had a large crack in the cover glass with associated cell delamination --

presumably shipping damage. Three small cover glass cracks and delamination above many cells were observed in the second module. Qualification testing was resumed on the latter and was completed satisfactorily. Two more M modules will be tested.

Ten Type K and six Type M modules were tested for temperature coefficients.

c. Commercial. Four Type CN modules were subjected to the standard temperature cycling test. These modules were encapsulated with Shell epoxy in a plastic frame. All four modules failed catastrophically; all cells were cracked, the encapsulant was hard, cracked, and peeled, and all circuits were open.

3. Field Testing

The activity this quarter can be summed up as one of consolidation. In addition to acquiring basic data, effort was devoted to: (1) improving operating procedures; (2) planning for future module deployments (Block III, Commercial, Task 4, dirt test); (3) writing an update report; and (4) developing plans for the solutions to some of the testing problems, such as the insolation reference problem.

During this quarter a controlled experimental program for acquiring data on the effects of soiling was inaugurated at the Pasadena site. Six 4 x 4 ft subarrays dedicated for this purpose were installed in the field on June 5. Four of the subarrays are made up of Block II modules, a fifth is made up of ARCO-Solar ripple glass modules, and a sixth, designated for long-term "dirt testing," is made up of Block II Solar Power and Spectrolab modules. The subarrays are being left in the field undisturbed for a month, then taken down and interrogated with the LAPSS system, washed (except for the long-term dirt subarray), and interrogated again. This cycle will be repeated monthly. The first results will be available in early July.

In an attempt to simulate a realistic life testing environment, the modules hooked to the data system have been placed under electrical load. Using the load junction option provided in the multiplexors, they have been wired together in series on a subarray basis along with a load resistor tailored to dissipate peak power at 85 mW/cm^2. Periodically, experimental power dissipation data will be obtained and compared with theoretical analyses. Modules at Table Mountain have also been placed under load; those modules at Goldstone will also be placed under load shortly.

An initial field status survey at the JPL Site was made in mid-February, using change in fill-factor as a measure of degradation. Since then this procedure has been upgraded, and during the period May 11 to May 31 an extensive survey was made. Special computer programs were written to control the interrogations and analyze the results. Between the 11th and 31st of May, 12 interrogations were made, which were compared with the fill-factors obtained before placing the modules in the field. The results are presented in Table 6-1, together with failure statistics.

Table 6-1. Module Experience at the JPL Site as of May 31, 1978

	Module Type	Quantity	Avg. Time in Field (Months)	% Fill-Factor Decrease in Field				Failed
				< 3	< 6	< 10	> 10	
BLOCK I	Sensor Tech	62	16	50	5	2	1	4
	Spectrolab	39	17	14	18	4	1	2
	Solarex	38	20	24	8	3		3
	Solar Power	21	17	5	1		2	13
BLOCK II	Sensor Tech	34	12	31	3			
	Spectrolab	13	9	13				
	Solarex	17	11	8	9			
	Solar Power	13	11	9	4			

4. Performance Measurements and Standards

Efforts on the photon effect were suspended this quarter. At this time ASI has virtually eliminated the effect from its Block III production modules; the most recent 10 modules exhibiting an effect of only 1.4%. In addition, Sensor Tech and Motorola modules no longer exhibit a significant effect, with measurements indicating 1% or less on the average. Solar Power's modules are now exhibiting a reduced photon effect of about 2%. No other vendors show any effect at this time. Control experiments were performed with all vendors, but primarily with ASI, in an effort to pinpoint the cause of the photon effect. The results of these experiments to date have failed to determine the cause of the photon effects. However, since the effect has been gradually diminishing with increased production experience to an almost negligible level in current Block III modules, further efforts to determine the cause have been suspended.

The testing and distribution of the Block III reference cells to all vendors has been completed. In the process, it was discovered that the reference cells exhibited light piping effects that affected the calibration value, depending on how the cells were used in the measurement process. A series of tests were performed at JPL and Lewis Research Center with the result that the calibration values of the Block III reference cells were raised 6.28%. All vendors have been notified of this change. This new calibration value is valid only under the condition that the reference cell is fully illuminated in the solar simulator.

The Block II/III reference cell intercomparison was completed for all vendors during this report period. The calibration ratios obtained were consistent with the values expected based on the change in the reference cell calibration standard atmosphere and the new international pyheliometric standard. Additional tests were performed on the Solarex high-density solar cells that indicated that the high-density modules could be tested with the same reference cell as the standard Solarex Block III production modules.

In an effort to allow Motorola to acquire an operational large area pulsed solar simulator (LAPSS) facility as early as possible, the LAPSS equipment originally scheduled for delivery to JPL in July was instead delivered to Motorola. This switch will delay JPL's LAPSS delivery until September; however, the facility is not expected to be available for occupancy before that time.

5. Failure Analysis

Activity during this quarter included the filing of 32 new problem/failure reports and the closure of 28 problem/failure analyses. Distribution of the failure and status reports was continued on a monthly basis to affected manufacturers and test application centers.

Development of failure analysis techniques is continuing as an on-going effort to improve problem cause identification for failed modules. The use of the Scanning Laser Beam Induced Current Output

equipment and Solar Cell Laser Scanner (SCLS) has been expanded to view as much as half a panel at one time, where previously only one cell was scanned at a time. The laser scan system is also progressing from a breadboard to a more refined configuration.

The analysis of corona and voltage breakdown has been improved with the delivery of a corona discharge tester that is capable of detecting partial discharge (corona) problems in insulating materials over the range of 0 V to 40,000 V. This equipment can differentiate between discharges caused by surface leakage and voids in materials.

B. TECHNICAL DATA

1. Large-Scale Production Task

a. Block III. The production detail for the quarter is displayed in the following table:

Contractor	kW Allocation	kW Shipped April-June	kW Total Shipped	% Complete
ARCO Solar, Inc.	35	3.76	3.76	10.7
Motorola, Inc.	50	0.10	0.10	0.2
Sensor Technology, Inc.	40	3.54	3.54	8.8
Solar Power Corp.	50	11.43	11.43	22.9
Solarex Corp.	30	17.17	22.39	74.6
Total	205	36.00	41.22	20.1

At the outset of the project, it was recognized that contractural adjustments would be required to accomodate differences in the calibration of Block II and Block III reference cells, since the Block II reference cells were the basis for the contractors' bid prices. Block III reference cells have been calibrated using a more recently adopted standard of radiant intensity, and certain errors present in the calibration of the Block II reference cells have been corrected. The resultant adjustment has been made during this quarter in contracts with ARCO Solar, Solar Power, and Solarex. The effect was to reduce the apparent power output of a module, thus requiring more modules to produce the amount of power desired. The amount of change varies among the contractors, from 6% to 9%. The Sensor Tech contract is in the process of being altered and the Motorola adjustment will be made once sufficient modules and appropriate reference cells are available.

Another perturbation that will affect all the contracts is the discovery of a systematic calibration error which has affected the

calibration of both Block II and Block III reference cells provided by Lewis Research Center. This error, when corrected, increases the apparent power output of the modules being tested. Contracts are in the process of being adjusted to reflect the increase in apparent power.

The average power output of the solar modules produced by ARCO Solar and Solar Power has been in excess of the projected nominal average power output established at the outset of the project, and the number of modules required to produce the desired amount of power has been reduced. These contracts have also been adjusted to reflect this increase in performance.

2. Failure Analysis

Table 6-2 summarizes module problem and failure experience during environmental, field test, and user application.

Table 6-2. Summary of P/FR Activity

Mfr.	Procurement Block	New P/FRs	Closed P/FRs	Environmental Test	Field Test	Application Centers
V	Block I		3		1	2
	Block II		5	2		3
W	Block I	4	2		2	3
Y	Block I	1	4		2	3
	Block II	6		6		
Z	Block I	9	9	2	6	8
	Block II	2	4	2		4
	Developmental (Task 4)	9		9		
	Commercial (Task 5)	5	1	5		1

Problem categories for P/FRs summarized in Table 6-2 are shown in Table 6-3.

Table 6-3. Problem Categories

Mfr.	Procurement Block	Modules with Electrical Degradation	Encapsulation Degradation	Total P/FRs	Comments
V	Block I	1	2	3	Open circuit, delamination.
	Block II	5		5	Open circuit, elect. degradation.
W	Block I	4	1	5	Elect. degradation, open circuit, voltage breakdown.
Y	Block I	3	4	5	Delamination, open circuit, degradation.
	Block III	2	4	6	Discoloration, cracked cells.
Z	Block I	15	14	16	Delamination, fractured interconnects, burned cells.
	Block II	4	2	6	Open circuit, elect. degradation, delamination, corrosion.
O, K, M, Y	Developmental (Task 4)	3	8	10	Cracked glass, open circuit, elect. degradation, entrapped air, delamination.
U, CN	Commercial (Task 5)		5	5	Elect. degradation, delamination.

a. Manufacturer V. The Block 1 module failures continue to show fractured interconnects and delamination of encapsulant.

Block II modules returned from the Nebraska irrigation site show cracked cells as the major problem of electrical degradation and open circuits.

b. Manufacturer W. Block I module failures relate to cracked cells causing either electrical degradation or open circuits.

c. Manufacturer Y. Field and application failures of the Block I modules were caused by work hardening and fracturing of interconnects and encapsulation delamination.

The Block III modules are exhibiting discoloration of the interconnects after environmental test. This problem is also being observed on Block II modules in field test and applications. Analysis will be conducted to determine if this is a long-term problem with respect to reliability of the modules.

The Task 4 (high density) module was found to have interconnect fractures. The expanded mesh interconnect material did not appear to provide the required stress relief when subjected to thermal cycling tests.

d. Manufacturer Z. The Block I failures from the field are mostly caused by inadequate stress relief of the interconnect, which causes open circuits; if series-connected to high voltages the module can exhibit a burned area where the interconnect is fractured.

Block II module failures include open circuits caused by cracked or broken cells, corrosion of thermal hardware, and encapsulant delamination in the area of the cell and interconnects. Some discoloration of interconnects has been observed in the field test site. The effect of the discoloration on the module reliability is being investigated.

e. Task 4. Developmental modules from three vendors were flagged with problem/failure reports. The problems observed include cracked glass and cell surface delamination and entrapped air in the encapsulant under the glass.

f. Task 5. Modules from two commercial manufacturers experienced problems in test. These modules experienced electrical degradation in one case and encapsulation failure in the other as the result of temperature stress.